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SPACECRAFT DEPARTMENT

MISSILE AND SPACE DIVISION

STUDY OF NUCLEAR BRAYTON CYCLE POWER SYSTEM (U)

CONCEPTUAL DESIGNS

9/28/72

Prepared for:

NAL AERONAUTICS AND SPACE ADMINISTRATION

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STUDY OF NUCLEAR BRAYTON CYCLE POWER SYSTEM (U)

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ABSTRACT

Conceptual designs were made of nuclear Brayton cycle powerplants for use on both manned and unmanned missions. The three-loop, 150 KWe, powerplant for use with a manned space station consists of; a 4π shielded, liquid metal cooled, reactor loop, a two-shaft, recuperative, power conversion loop, and a NaK filled radiator loop. The specific weight is 185 lbs/KWe (initial launch configuration) with replacement powerplants weighing 110 lbs/KWe. The 200 KWe powerplant for a scientific probe is a one-loop system using neon as the working fluid and weighs 52 lbs/KWe.

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TABLE OF CONTENTS

Section			Page
1	INTRODUCTION		1-1
2	SUMMARY		2-1
3	POWERPLANT ANALYSIS		3-1
	3.1	Component Models	3-1
		3.1.1 Radiator Models	3-2
		3.1.1.1 NaK-filled Radiators	3-2
		3.1.1.2 Gas-filled Radiators	3-4
		3.1.2 Reactors	3-5
		3.1.3 Shielding	3-6
		3.1.4 Heat Exchanges	3-9
		3.1.5 System Ducting	3-11
	3.2	System Design	3-11
		3.2.1 System Configuration	3-11
		3.2.2 Parametric Results	3-13
	3.3	Radiator Structural Model	3-15
		3.3.1 Load Carrying Elements	3-15
		3.3.2 Parasitic Weight	3-18
	3.4	Area Limit Model	3-20
		3.4.1 Mean Time to Failure Model	3-20
	3.5	Startup	3-22
4	CONCEPTUAL DESIGN OF A POWERPLANT FOR A MANNED SPACE STATION		4-1
	4.1	Configuration Description	4-2
	4.2	System Weight Variation with Radiator Area	4-11
	4.3	Radiator Design	4-18
	4.4	Recuperator and Heat Exchanger Design	4-18
	4.5	Sensitivity to Off-Optimum Operation	4-22
	4.6	Maintenance, Reliability, and Redundancy	4-36
		4.6.1 Redundant Components within Loops	4-39
		4.6.2 Redundant Loops	4-43
5	SCIENTIFIC PROBE POWERPLANT CONCEPTUAL DESIGN		5-1
	5.1	200 KWe Unmanned Configuration Description	5-2
	5.2	System Weight Variation with Radiator Cone Angle	5-9
	5.3	Radiator Design	5-15
		5.3.1 Radiator Thermal Analysis	5-15
		5.3.2 Radiator Structural Analysis	5-20
	5.4	Recuperator Design	5-25
	5.5	Off-Optimum Performance	5-26
		5.5.1 Effect of Reactor Diameter	5-28

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ATOMIC ENERGY ACT 1954

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LIST OF ILLUSTRATIONS

Figure No.	Title	Page
2-1	150 KWe 3 Loop Brayton Cycle Powerplant for Manned Space Station	2-3
3-1	Shadow Shielding for Unmanned Missions	3-6
3-2	Typical Shield Configuration for Spoke-Mounted Powerplant on Three-Arm Station	3-8
3-3	Shield Weight -Spoke-Mounted Powerplant on Three-Arm Space Station	3-9
3-4	Loop Arrangement	3-12
3-5	Specific Weight of Optimized Powerplants--Unmanned Applications	3-13
3-6	Summary of Performance of Brayton Cycle Powerplants for Use with Manned Space Station--Three Loop Systems, Dual Redundancy	3-14
3-7	Radiator Structural Requirements	3-16
3-8	Assumed Equivalent Loading Curves	3-19
3-9	Weight Requirements for Area Limited Radiators	3-21
3-10	Mean Time to Failure Requirements	3-23
3-11	Effect of Mean Time to Failure on Radiator Weight	3-24
4-1.	Brayton Cycle 150 KWe Manned System	4-3
4-2.	Radiator Shield Configuration	4-6
4-3.	Powerplant Disposal Technique	4-7
4-4.	Effect of Survival Probability on Powerplant Specific Weight	4-10
4-5.	Variation of Initial Launch Specific Weight with Primary Radiator Area	4-14

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RESTRICTED DATA
ATOMIC ENERGY ACT 1954

CONFIDENTIAL
RESTRICTED DATA

Figure No.	Title	Page
4-6.	Variation of Replacement Powerplant System Weight with Primary Radiator Area	4-15
4-7.	Variation of Effective System Weight with Primary Radiator Area	4-16
4-8.	Variation of Radiator Weight with Area Limit	4-17
4-9.	Variation of Specific Weight with Increase in Reactor Core Diameter	4-24
4-10.	Variation of Specific Weight with Reactor Side Heat Exchanger Pressure Loss Ratio	4-25
4-11.	Variation of Specific Weight with Reactor Side Heat Exchanger Effectiveness	4-26
4-12.	Variation of Specific Weight with Turbine Pressure Ratio	4-27
4-13.	Variation of Specific Weight with Compressor Inlet Temperature	4-29
4-14.	Variation of Specific Weight with Recuperator Pressure Loss Ratio (Each Side)	4-30
4-15.	Variation of Specific Weight with Recuperator Effectiveness	4-31
4-16.	Variation of Specific Weight with Radiator Side Heat Exchanger Pressure Loss Ratio	4-32
4-17.	Variation of Specific Weight with Radiator Side Heat Exchanger Effectiveness	4-33
4-18.	Variation of Specific Weight with Interconnecting Pipe Diameter	4-34
4-19.	Variation of Specific Weight with Reactor Loop Temperature Rise	4-35
4-20.	Variation of Specific Weight with Parasitic Pressure Losses	4-37
4-21.	Variation of Specific Weight with Sink Temperature	4-38

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RESTRICTED DATA
ATOMIC ENERGY ACT 1954

CONFIDENTIAL
RESTRICTED DATA

LIST OF ILLUSTRATIONS (CONT)

Figure No.	Title	Page
4-22.	Redundant Components Within Loops	4-40
4-23.	Redundant Loops	4-40
4-24.	Reliability of Parallel Components with Second Component in Standby.	4-42
4-25.	Reliability of Parallel Components with Both Components Operating..	4-42
5-1.	Conceptual Design of Brayton Cycle Power Plant for Unmanned Scientific Probe	5-5
5-2.	Primary Radiator Area Variation with Cone Angle (200 KWe Vehicle)	5-10
5-3.	System Weight Variation with Cone Angle 200 KWe Unmanned System with Uniformly Fuel Loaded Reactor	5-11
5-4.	System Weight Variation with Cone Angle-200 KWe Unmanned System with Power-Flattened, Uniform-Diameter Cooling Passage Reactor	5-12
5-5.	Radiator Weight Variation with Cone Angle-200 KWe Unmanned System with Uniform-Fuel Loaded Reactor	5-13
5-6.	Radiator Weight Variation with Cone Angle-200 KWe Unmanned System with Power-Flattened, Uniform-Diameter Cooling Passage Reactor	5-14
5-7.	Piping Schematic of 200 KWe Unmanned System-Primary Radiator Loop	5-18
5-8.	Radiator Structural Loading	5-19
5-9.	Section Nomenclature	5-23
5-10.	Recuperator Design	5-29
5-11.	Sensitivity of System Specific Weight to Reactor Fractional Pressure Drop-Uniform Fuel Loaded Reactor	5-30
5-12.	Sensitivity of System Specific Weight Turbine Pressure Ratio-Uniform Fuel Loaded Reactor	5-30

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ATOMIC ENERGY ACT 1954

CONFIDENTIAL
RESTRICTED DATA

LIST OF ILLUSTRATIONS (CONT)

Figure No.	Title	Page
5-13.	Sensitivity of System Specific Weight to Compressor Inlet Temperature-Uniform Fuel Loaded Reactor	5-30
5-14.	Sensitivity of System Specific Weight to Radiator Fractional Pressure Drop-Uniform Fuel Loaded Reactor	5-31
5-15.	Sensitivity of System Specific Weight to Recuperator Effectiveness-Uniform Fuel Loaded Reactor	5-31
5-16.	Sensitivity of System Specific Weight to Recuperator Pressure Drop (Each Side) - Uniform Fuel Loaded Reactor	5-31
5-17.	Sensitivity of System Specific Weight to Interconnecting Pipe Diameter-Uniform Fuel Loaded Reactor	5-32
5-18.	Sensitivity of System Specific Weight to Reactor Fractional Pressure Drop-Power Flattened Reactor	5-32
5-19.	Sensitivity of System Specific Weight to Turbine Pressure Ratio-Power Flattened Reactor	5-32
5-20.	Sensitivity of System Specific Weight to Compressor Inlet Temperature -Power Flattened Reactor	5-33
5-21.	Sensitivity of System Specific Weight to Radiator Fractional Pressure Drop-Power Flattened Reactor	5-33
5-22.	Sensitivity of System Specific Weight to Recuperator Effectiveness-Power Flattened Reactor	5-33
5-23.	Sensitivity of System Specific Weight to Recuperator Pressure Drop (Each Side)-Power Flattened Reactor	5-34
5-24.	Sensitivity of System Specific Weight to Interconnecting Pipe Diameter-Power Flattened Reactor	5-34
5-25.	Sensitivity of System Specific Weight to Parasitic Pressure Losses-with Power Flattened Reactor or with Uniform Fuel Loaded Reactor	5-34
5-26.	Sensitivity of System Specific Weight to Sink Temperature-with Power Flattened Reactor or with Uniform Fuel Loaded Reactor	5-35
5-27	Effect of Reactor Diameter on System Weight	5-36

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1. INTRODUCTION

Much interest exists in the use of Brayton cycle powerplants for use as space power supplies. The radiator area requirements for a Brayton cycle powerplant are quite sensitive to the cycle fractional pressure loss and recuperator effectiveness. Accurate component designs, performance analyses, and weight evaluations are required in order to determine the specifications for a minimum weight system. Particular attention must be paid to the influence of the payload shielding requirements on the reactor size and radiator geometry, and the structural requirements of the radiator. The designs presented herein have examined these points in detail.

The component specifications of the powerplant designs are those corresponding to a minimum weight complete system. Optimizations were made of the complete powerplant weight with respect to each independent cycle variable. Vehicle integration, structural, and other engineering design and construction details have been included in the optimization tradeoffs. The development of a Brayton cycle powerplant will undoubtedly require component and systems development in order to demonstrate the reliability required before the commitment of a mission. This study is intended to provide guidelines for such a program.

An analysis and conceptual design of nuclear Brayton cycle powerplants has therefore been made. The designs are based on the use of a liquid-metal cooled reactor operating at a 1900^{o}F maximum clad temperature, and a neon-cooled reactor operating with a coolant discharge temperature of 2200^{o}F. The latter temperature has been selected on the basis of using an uncooled refractory metal turbine. The objectives of this study includes an evaluation of the weight, performance, and specifications of completely engineered nuclear Brayton cycle powerplants, for two specific space missions.

Phase I of this study* reported parametric data describing optimized powerplants over a range in power from 50 to 200 KWe, and a range in turbine inlet temperatures from 1450 to 2200^{o}F. This report describes the conceptual designs.

*Study of Nuclear Brayton Cycle Power Systems, NASA CR-54397, GE 65SD4251, July 1965.

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2. SUMMARY

This report describes the results of Phase II, NASA Contract NASw-980, entitled "Study of Nuclear Brayton Cycle Power System." During this phase of the study conceptual designs of two nuclear Brayton cycle powerplants were generated. The missions considered were:

1. A manned orbiting spacecraft (Figure 2-1), requiring 150 KWe, where the power is used primarily for on-board electrical requirements (non-propulsion).

2. An unmanned interplanetary probe, requiring 200 KWe, where the power is used for both instrumentation and terminal electrical propulsion.

Emphasis has been placed on the nuclear reactor and shield, the radiator, and powerplant arrangement. Phase I of the program* consisted of a parametric evaluation of various system configurations, including single-, two-, and three-loop arrangements with different combinations of liquid and gas cooled reactors and radiators. The specific systems selected for the conceptual designs are:

1. A three-loop, liquid metal cooled reactor and radiator with redundant power conversion equipment was selected for the manned space station application.

2. A one-loop, all-gas system was selected for the unmanned scientific probe application.

The liquid-metal cooled reactor was selected for the manned space station application since it could be built with the smallest diameter, which results in a considerable savings in (4π) shield weight. The separate reactor loop provides for isolation of any primary loop radioactivity due to coolant activation, fuel element leakage, or activated transported contaminants. A release of 10^{-5} of the total fission product inventory would produce excessive crew dose.

*Study of Nuclear Brayton Cycle Power Systems, NASA CR-54397, GE 65SD4251, July 1965.

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150 KWe

3 LOOP BRAYTON CYCLE POWER PLANT FOR MANNED SPACE STATION

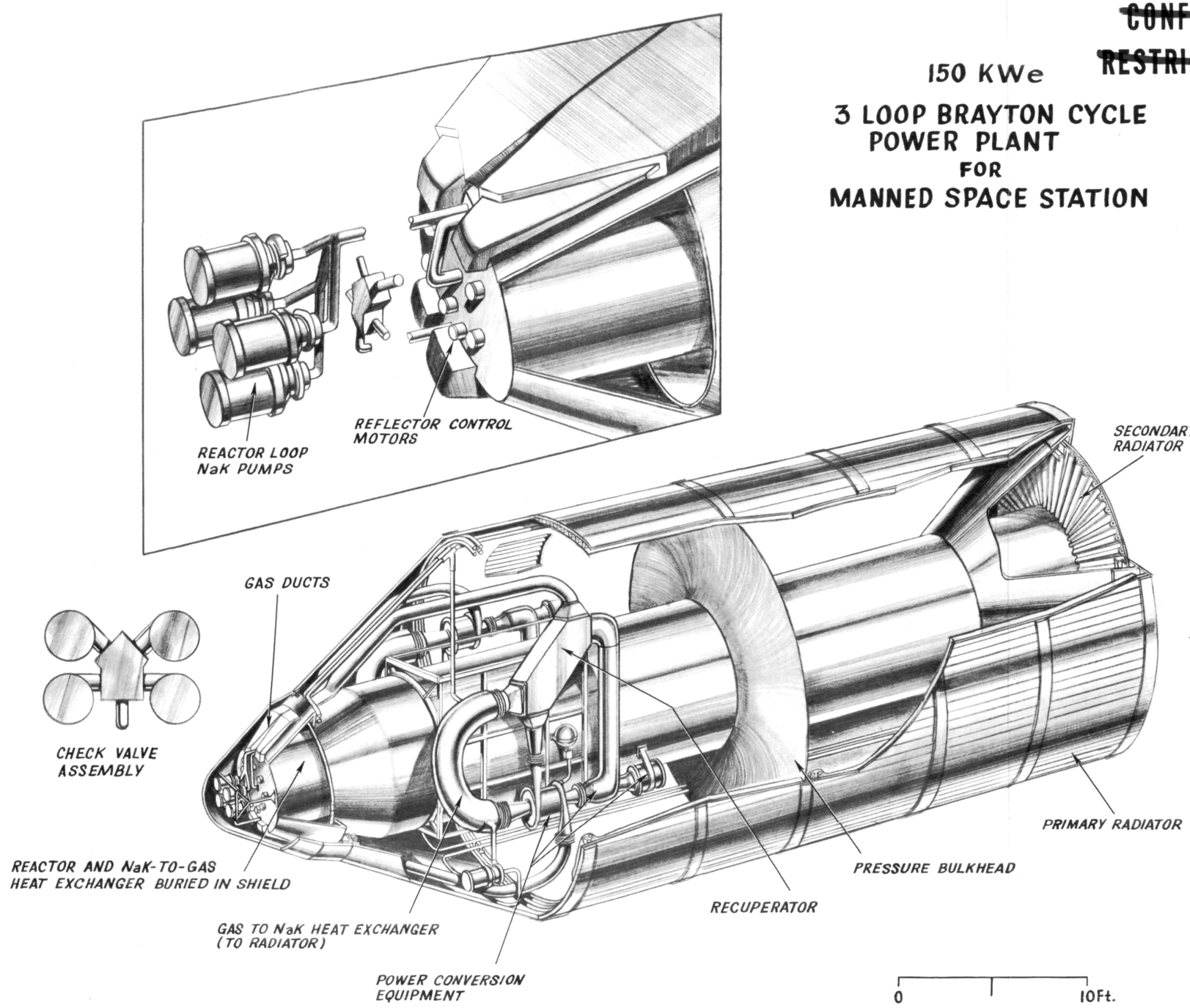

Figure 2-1. 150 KWe 3 Loop Brayton Cycle Powerplant for Manned Space Station

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The NaK-to-gas heat exchanger requires less volume than a gas-to-gas heat exchanger, again saving shield weight. A separate reactor loop can be used to provide redundant power conversion loops, especially desireable in manned systems. The separate radiator loop results in a weight savings over a gas-filled radiator at the turbine exhaust pressure level. The shared fin radiator approach results in full heat rejection capability for each power conversion loop.

The all-gas, single-loop, system was selected for the unmanned scientific probe mission since gas-cooled UO_2-W cermet reactor systems operating at 2200^{o}F turbine inlet temperature result in lighter systems than was found for the other reactors considered for this mission. The selection of an all-gas system was based on the mission requirement of start-up 10,000 hours after launch, and the attendant freezing problems associated with liquid radiators. The loop activation due to fission product leakage is not significant with unmanned payloads, and the effect of reactor diameter on shield weight is less since only shadow shielding is required and the payload can tolerate a higher radiation dose.

Component designs are described for the reactor, shield, turbomachinery, heat exchangers, ducting, and radiators. Shielding and radiator structural requirements result in significant weight advantages for systems using higher fin efficiencies than are required by independently optimized radiators. The powerplant for the manned space station is designed to be launched by the Saturn IB booster, while the powerplant for the unmanned vehicle is launched by a Saturn V. A structural analysis of the radiators was made for both powerplants and necessary reinforcements were provided so that the radiator provides sufficient rigidity to support the entire powerplant, including reactor and shielding, during launch. The powerplant for the unmanned spacecraft also serves as the payload structure. A typical 3000 lb. payload for a Jupiter orbiter is shown. The influence of radiator survival probability or mean time to failure, on powerplant weight is shown.

The specific weight of the three-loop powerplant using a 1900^{o}F maximum clad liquid metal cooled reactor, for the manned space station is 185 lbs/KWe, when the entire shield is launched with the powerplant. Replacement powerplant installations in space would weigh

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110 lbs./KWe since they would utilize a large portion of the original shield, which would be permanently attached to the space station. The effective weight of a powerplant based on five uses of the permanent section of the shield is 122 lbs./KWe.

The specific weight of the one-loop powerplant for the unmanned scientific prove is 52 lbs/KWe, based on the use of uniformly fueled, temperature flattened, (variable sized coolant passengers) UO_2-W cermet reactor. The same system using a powerflattened reactor with uniform sized coolant passages is 74 lbs./KWe.

All powerplants shown are optimized. The influence of off-optimum designs are presented. The effects of parasitic pressure drop, sink temperature, and radiator survival probability on powerplant specific weight are shown.

The tubomachinery used is modeled after the NASA solar Brayton cycle turbomachinery, with the pressure level increased in proportion to the power level. Total-to-total compressor and combined compressor and alternator drive turbine efficiencies of 80 and 87% were used. This selection is based on the advantages of having a high system pressure in the reactor, or primary heat exchanger, whereby smaller shields are required. Neon is used as the working fluid in both systems. Use of argon would result in larger and heavier reactors, heat exchangers, and radiators, and would require heavier shielding. Optimization of the system resulted in the selection of a pressure ratio somewhat lower than that of the solar Brayton cycle, however, no attempt was made to correct the turbomachinery performance for the lower pressure ratio, or different molecular weight of the working fluid.

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3. POWERPLANT ANALYSIS

A powerplant model was created in order to determine the influences of component configuration and performance on system weight. Reference component designs, and parametric variations of them, were made, and correlations developed for the performance of each subsystem in terms of the pertinent variables. Temperature levels, temperature drops, pressure levels, fractional pressure drops, effectiveness, shielding angles, thermal power, and electrical power were the component interface and performance variables. A powerplant performance evaluation program was developed which determined the weight of the entire system with the temperatures and pressures at each component interface matched. The powerplant optimization consisted of systematically varying each of the system component interface variables until the weight was minimized with respect to that variable. By repeated application of this procedure a powerplant configuration was arrived at for which variations of any of the cycle variables would result in a weight increase of the system. These cycle variables were then used as design objectives for the individual components. The detailed design of the components permitted an evaluation of the scaling laws used in the overall performance program. The agreement of the initial weight estimates and the final design weights were excellent. The complete powerplant evaluation program essentially determines the value of the component interface variables such that the derivative of system weight with respect to every independent variable is zero. The results of the parametric analysis and system optimizations were previously reported.

3.1 COMPONENT MODELS

The chief components of a nuclear Brayton cycle powerplant are:

- Reactor
- Shield
- Radiator
- Turbomachinery
- Heat exchangers

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- Alternator
- Ducting
- Controls

Designs of the reactor, shield, radiator, heat exchangers, and ducting were generated during this study. The turbomachinery and alternator performance were fixed at values previously agreed upon. Control functions were identified but the electrical equipment necessary to perform these functions was not designed.

3.1.1 RADIATOR MODELS

Models of radiators filled with both NaK and gas were made by correlating a large number of individual designs. The reference conditions for the correlations are:

1. 95% survival probability for 10,000 hours
2. Emissivity, 0.9
3. Sink temperature, -10°F
4. Unlimited area
5. Structure requirements not included
6. Temperatures between 1000°F and 150°F
7. Aluminum fins and tubes, with steel liners, below 700°F; steel tubes and steel/copper fins above 700°F

The effects of variations in the first, third, fourth, and fifth reference conditions were also evaluated. Both neon and argon were used in the gas radiator model.

3.1.1.1 NaK-Filled Radiator

The correlations for the NaK-filled radiators are:

$$RSW = \Phi + e^{(0.2516 \ln (\text{Area}) + 0.00138\, T_{eff} - 3.071)}$$

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$$\text{Area} = \frac{1.99 \times 10^{12} Q}{(T_{eff}^4 - T_s^4)\, \varepsilon \eta_{fin}}$$

where

RSW = Radiator specific weight, lbs/ft^2

Area = Radiator area, ft^2

Q = Thermal load, KW

T_{eff} = Effective radiating temperature, °R

ε = Emissivity

η_f = Fin efficiency (NaK filled, unlimited area, radiators optimized with fin efficiencies of 0.70 to 0.73)

Φ = Factor to account for the steel/copper portion of the radiator

$$\Phi = \frac{\left(\frac{T_{in}\,(°R)}{1160}\right)^3 - 1}{\left(\frac{T_{in}\,(°R)}{T_{out}\,(°R)}\right)^3 - 1} \qquad \text{for } T \geq 1160°R$$

$\Phi = 0.0$ for $T_{in} < 1160°R$

$$\frac{T_{eff} + \theta}{T_{sink}} = \overline{U}$$

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$$\frac{T_{in}}{T_{sink}} = U_i$$

$$\frac{T_{out}}{T_{sink}} = U_o$$

$$\bar{U}^4 = \frac{4\,(U_i - U_o)}{\ln\left[\left(\frac{e^{2\tan^{-1}U_o}}{e^{2\tan^{-1}U_i}}\right)\left(\frac{U_o+1}{U_i+1}\right)\left(\frac{U_i-1}{U_o-1}\right)\right]} + 1$$

θ = Film drop correlation factor

$\theta = 0.03\,T_{in} - 23.8 \quad 1160 \leq T_{in}\ (°R) \leq 1460$

$\theta = 11.0\ T_{in}\ (°R) < 1160$

3.1.1.2 Gas-Filled Radiators

Both neon and argon filled radiators were examined. The gas pressure in the model is proportional to the heat load. This scaling is based on the assumption that the cycle pressure level will vary in proportion to the power level. This in turn is based on an expectancy that the optimum cycle efficiency will not vary with power level or turbine inlet temperature. The correlation is based on the following normalized condition:

$P_{\text{inlet to radiator}} = 152.5$ psia

$Q_{\text{rejected by radiator}} = 725$ KWT

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Thus

$$P\ (psia) = 0.21\ Q\ (KWT)$$

Radiator weights and areas with and without internal fins (vanes) were evaluated. A comparison of optimum radiators for identical inlet and outlet conditions with aluminum tubes and external fins, and nickel liners and internal fins shows simultaneous weight and area reductions of 14 to 16%. With magnesium tubes and internal fins (no liner) the savings are both in excess of 20%. The correlations summarized here are for a neon filled aluminum/nickel model with internal fins.

$$RSW = e^{\left[(-0.1352\ \ell n\left(\frac{\Delta p}{p}\right) + 0.00058\ T_{out} - 0.822)\right]}$$

$$T_{eff} = 250\left(\frac{\Delta p}{p}\right) + 1.4\ T_{out} + 0.666\ T_{in} - 5.33 \times 10^{-4}\ (T_{in} - T_{out}) - 486$$

$$\eta_{fin} = 0.77 - 7.33 \times 10^{-5}\ T_{sink}$$

T_{out} = Radiator discharge temperature, °R

T_{in} = Radiator inlet temperature, °R

The same relationship between radiator area, effective radiator temperature and sink temperature applies as is used in the NaK filled radiator. Typical unlimited area radiators optimize with fin efficiency of 81%. Argon radiators were evaluated and were found to be 69% heavier than neon radiators for identical inlet and exit temperatures, pressures, and volume flows.

3.1.2 REACTORS

The details of the reactor nuclear, thermal, and hydraulic design are contained in a separate classified report.* The results summarize the reactor core diameter--reactor overall

* NASA CR-54398

pressure drop tradeoff relationships used in the system optimization. The basic reactor types are:

- Liquid metal cooled--UC fueled Cb-1Zr clad, with 1900°F maximum clad temperature

- Gas cooled--UO_2/W cermet, refractory clad, with 2200°F maximum gas discharge temperature

3.1.3 SHIELDING

The unmanned powerplant requires only shadow shielding. Figure 3-1 shows the shielding requirements for a 15° shield cone half angle for payload doses of 10^{11} n.v.t. and 10^{6} rad gamma. The shield model includes attenuation of both neutrons and gammas by both the lithium hydride and tungsten. Shielding is provided from the central ray to the outermost ray extending from the reflector corner to the outer edge of the payload. The powerplant

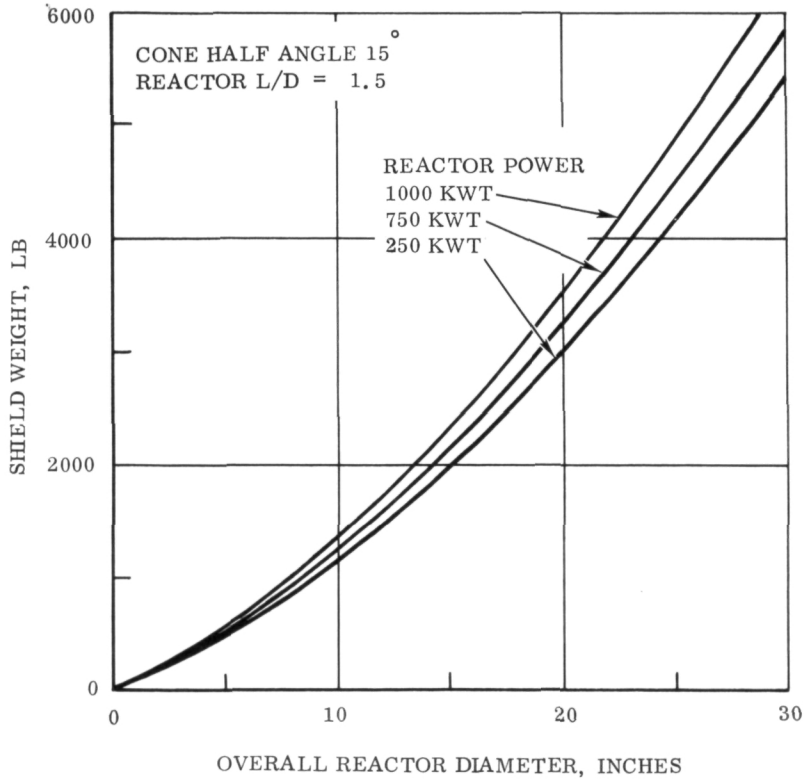

Figure 3-1. Shadow Shielding for Unmanned Missions

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optimization program contains a complete model of the shield so that changes in shield weight resulting from variations in reactor thermal power, reactor length and diameter, and cone angle are included in the overall system weight. Thus variations in system performance affecting radiator area, cycle efficiency, or reactor diameter are evaluated in a manner consistent with the shield requirements.

The shield concept for the powerplant for the manned space station application is shown in Figure 3-2. The shield is divided into two sections, one consisting of the large base and the triangular portions outside of the heat exchanger, and a smaller section between the heat exchanger and the reactor and between the reactor and the control drum actuators. The smaller section is attached to the reactor, heat exchanger, gas ducting and powerplant. The large cup-shaped section is permanently attached to the space station. When the powerplant is replaced the permanant section remains attached to the space station while the reactor, power conversion equipment, radiator and replacement section of the shield slip off the space station boom. The replacement powerplant slips over the boom like an arrowhead on a shaft. For further details of the replacement sequence see Figure 4-3.

Thus replacement powerplants need only have the small section of the shield adjacent to the reactor. This is typically 15% of the total shield weight. The weights reported in Section 4 of this report are labeled "replacement launch specific weight", "initial launch specific weight", and "effective specific weight", and refer respectively to the sum of the unshielded powerplant specific weight, the replacement shield specific weight, and either (initial launch specific weight) the entire permanent section of the shield, or (effective specific weight) 1/Nth of the permanent section of the shield. Unless otherwise noted the amortization is based on 5 uses of the permanent section of the shield.

The total shield weight is shown in Figure 3-3 as a function of the reactor diameter (including reflector) for two reactor power levels and two values of the total volume of primary heat exchangers. The sensitivity to physical and power size results in a weight advantage for efficient systems, and for compact reactors. The influence of primary heat exchanger volume on shield weight results in a shield weight penalty for low pressure drop and high effectiveness heat exchangers, which must be balanced by the influence of these parameters

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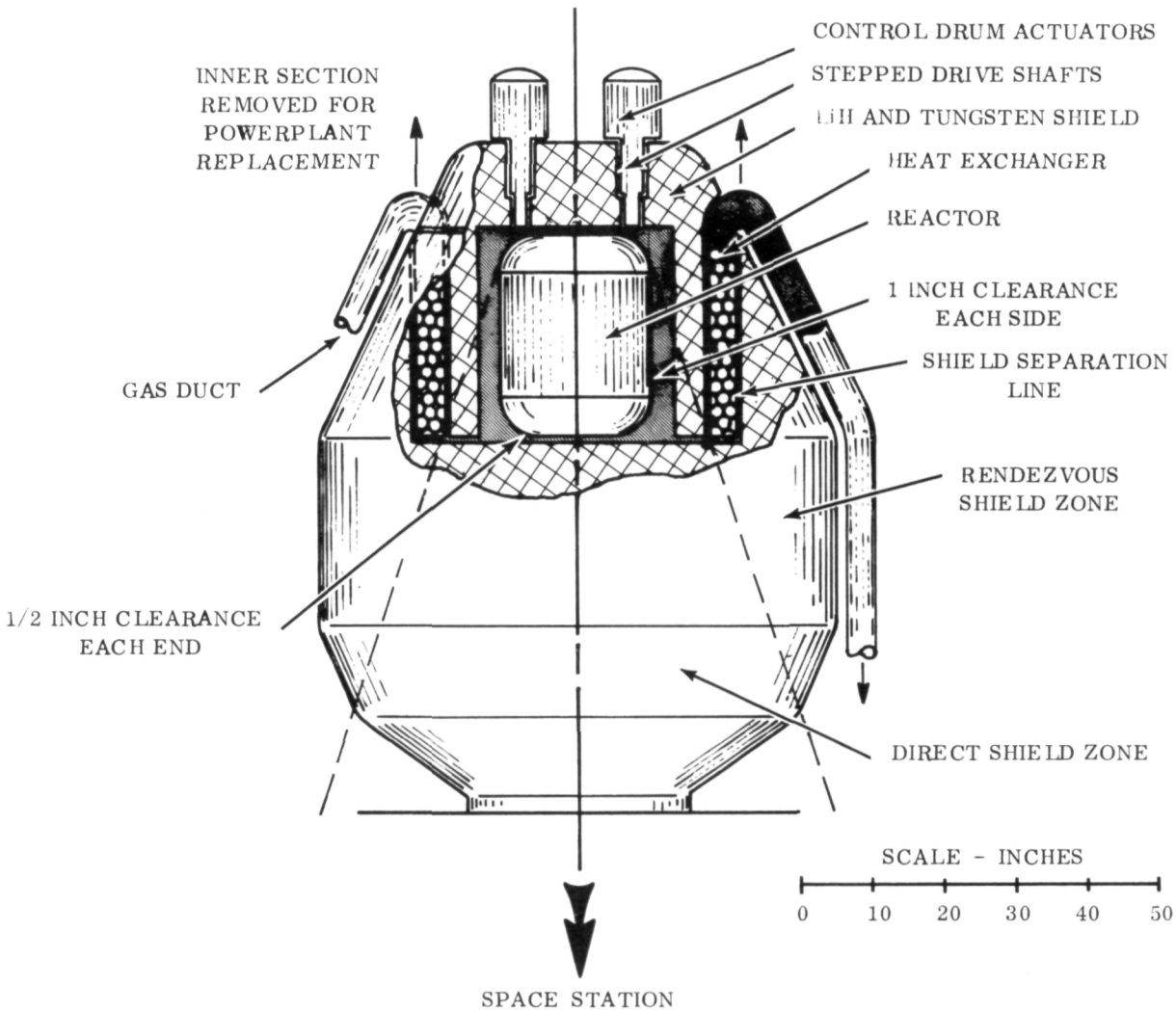

Figure 3-2. Typical Shield Configuration for Spoke-Mounted Powerplant on Three-Arm Station

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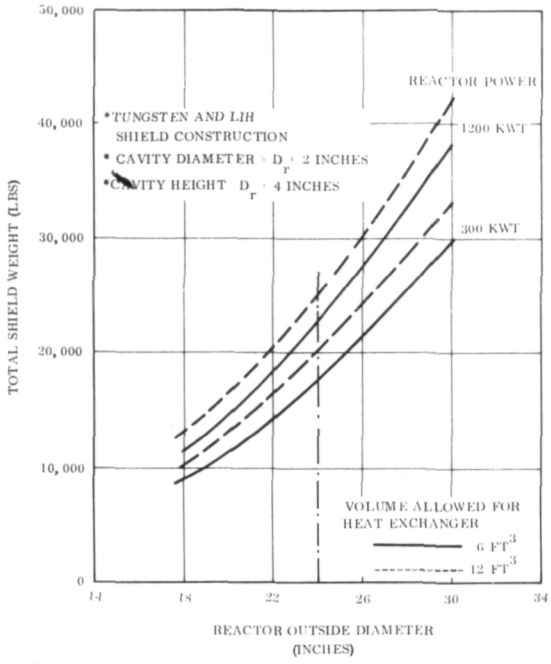

Figure 3-3. Shield Weight--Spoke-Mounted Powerplant on Three-Arm Space Station

on radiator size as well as reactor thermal power. Thus it is seen that many of the system variables affect the shield weight.

3.1.4 HEAT EXCHANGERS

Brayton cycle powerplants can use heat exchangers in three locations. A recuperator is valuable in returning waste heat in the turbine exhaust to the compressor discharge, thereby reducing the radiator area and reactor thermal power. Since both of these temperature changes of the working fluid must occur in order to complete the cycle, the cost of these processes in terms of the weight of some heat transfer equipment and the associated pressure drop must appear someplace. Evaluation of one case (that of the 200 KWe single-loop unmanned vehicle powerplant) showed a 28 lbs/KWe increase in weight when the recuperator was eliminated. When a recuperator is used it is possible to use an all-aluminum radiator.

The large gas boundary layer temperature drop at the hot end of the radiator, where the heat fluxes are highest due to the high rate of radiative heat transfer from the surface, results

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in the maximum difference between the gas and tube wall temperatures. The optimum radiator inlet temperature with a recuperator is 849°F, and the maximum radiator armor temperature is below 700°F, due to the large film drop, and an all-aluminum radiator is possible. However, the radiator inlet temperature without a recuperator is in excess of 1400°F and the wall temperature would be about 1200°F, prohibiting the use of aluminum. Such high temperatures would require a basically heavier steel/copper radiator. It is for these reasons that the recuperator is required.

Additional heat exchangers may be used to isolate the primary (reactor) and radiator loops. In the design for the manned space station an isolated primary loop was required and a weight advantage existed for a separate radiator loop, so that heat exchangers were found at three locations in that system. The models of the heat exchangers consisted of the weight being proportional to the surface area. The surface area was related to the effectiveness and pressure drop according to the type of heat exchanger.

Reactor loop heat exchanger

$$Wt \propto \left[\ln\left(\frac{1}{1-E}\right)\right]^{3/2} \left(\frac{\Delta p}{p}\right)^{-1/2}$$

Recuperator

$$Wt \propto \left(\frac{E}{1-E}\right)^{3/2} \left(\frac{\Delta p}{p}\right)^{-1/2}$$

Radiator loop heat exchanger

$$Wt \propto \left(\frac{E}{1-E}\right)^{3/2} \left(\frac{\Delta p}{p}\right)^{-1/2}$$

The models included equal fractional pressure drops on both sides of the recuperator, equal temperature change of the NaK and working fluid in the radiator loop heat exchanger, and isothermal NaK at its average temperature in the reactor loop heat exchanger.

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The scaling was done on the basis of wetted area, with the results normalized to reference designs.* Final heat exchanger weights were obtained by detail design and weight evaluation of the heat exchanger specifications resulting from the cycle optimization. The anticipated weights and sizes, and the final design values were basically in agreement. Pressure drops and weights of inlet and exit headers were included and amounted to an appreciable portion of the totals, as was found for the solar Brayton cycle equipment.

3.1.5 SYSTEM DUCTING

A model of the system ducting was made relating the length, diameter, and weight of the gas ducts. The allowable stress in the hot reactor return line was set at a value of 5000 psi and at a value of 10,000 psi for the cooler reactor feed line. The fractional pressure drop was found to be proportional to $1/D^4$. Since the wall stress level is proportional to the pressure, and the system pressure is proportional to the power level, the weight of the pipe is proportional to the product of LD^2 and the system power. The system optimization program trades off changes in duct weight and pressure drop to determine the optimum duct size. The various ducts are all designed to have the same Mach number, and hence equal fractional pressure drops per unit length. The optimum duct Mach number is 0.039.

3.2 SYSTEM DESIGN

3.2.1 SYSTEM CONFIGURATION

The powerplant may be arranged in one-, two- or three-loop configurations. Gas cooled reactors were used as the heat sources for the one- and two-loop systems, thereby evaluating the effect of a separate radiator loop. Comparison of two- and three-loop systems shows the effects of replacing a gas cooled reactor with a liquid-metal cooled reactor and a heat exchanger, for the condition of the same maximum clad temperature. Figure 3-4 shows the loop arrangements considered.

* Anderson, A. F., Felszeghy, S. F., "Parametric Design Study Recuperator Development Program Solar Brayton Cycle System", NAS 3-2793, Report L-9372, Ai Research, Los Angeles, March, 1964.

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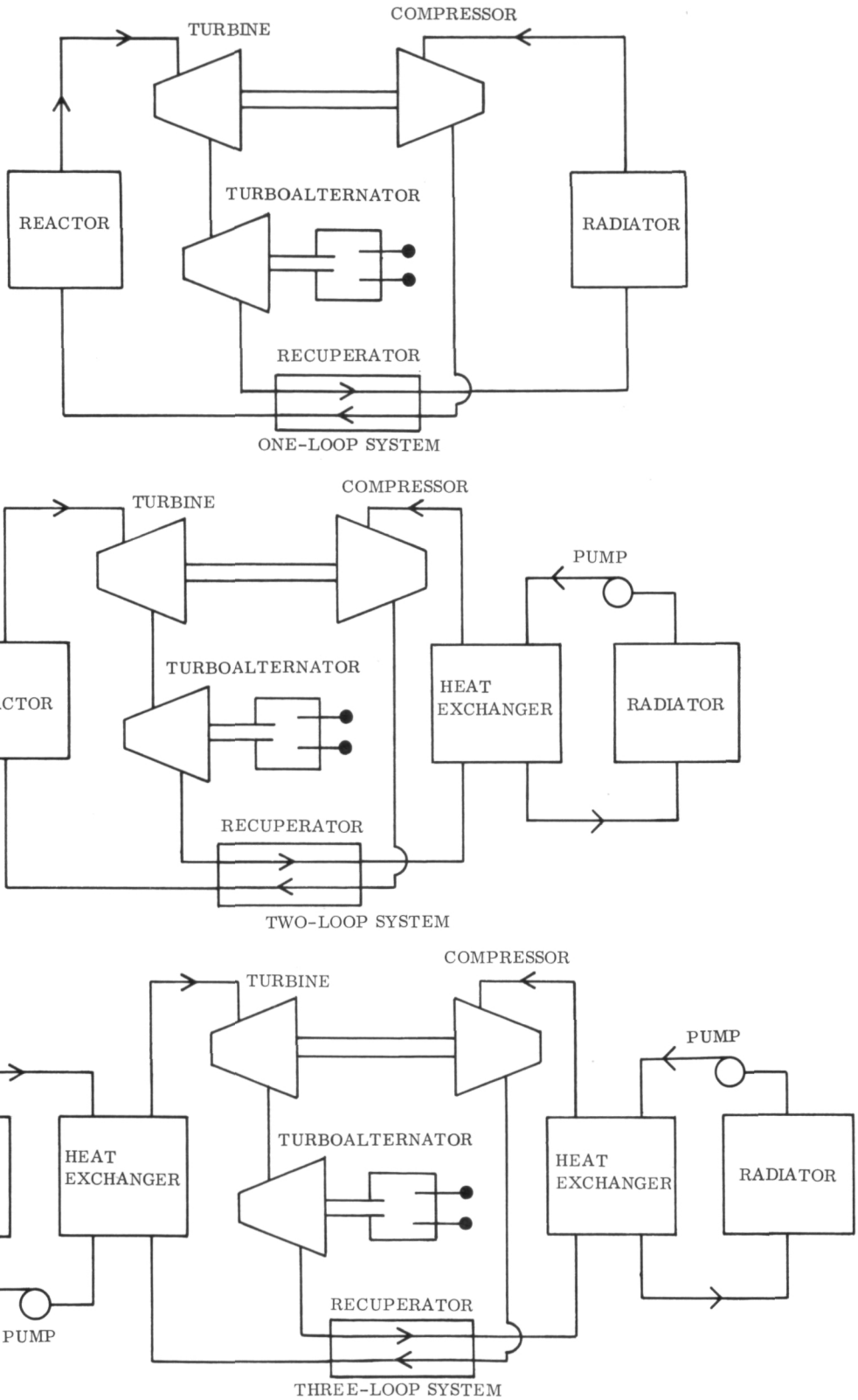

Figure 3-4. Loop Arrangement

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3.2.2 PARAMETRIC RESULTS

The results of phase I, parametric analysis, are reported in detail in Section 7 of the previous report, "Study of Nuclear Brayton Cycle Power System."* Overall system and component specific weights and radiator area requirements are shown as functions of system power level and turbine inlet temperature. Cycle efficiencies and component performance specifications are also given. Figures 3-5 and 3-6, shown here, summarize the more significant results of the parametric study.

The specific weights of powerplants for unmanned missions, with shadow shields designed for 10^{11} n.v.t. and 10^{6} rad gamma dose at the payload interface plane, are shown in Figure 3-5. The turbine inlet temperatures shown are the highest values considered for the various reactor types. It is seen that the addition of a radiator loop always results in a savings in specific weight. The effect of increasing turbine inlet temperature is similarly seen to result in a weight decrease. Both power flattened, and partially power flattened cermet cores were examined in phase I for use in the one-loop system. During the phase II design effort additional attention was paid to methods of reducing the reactor and shield diameter

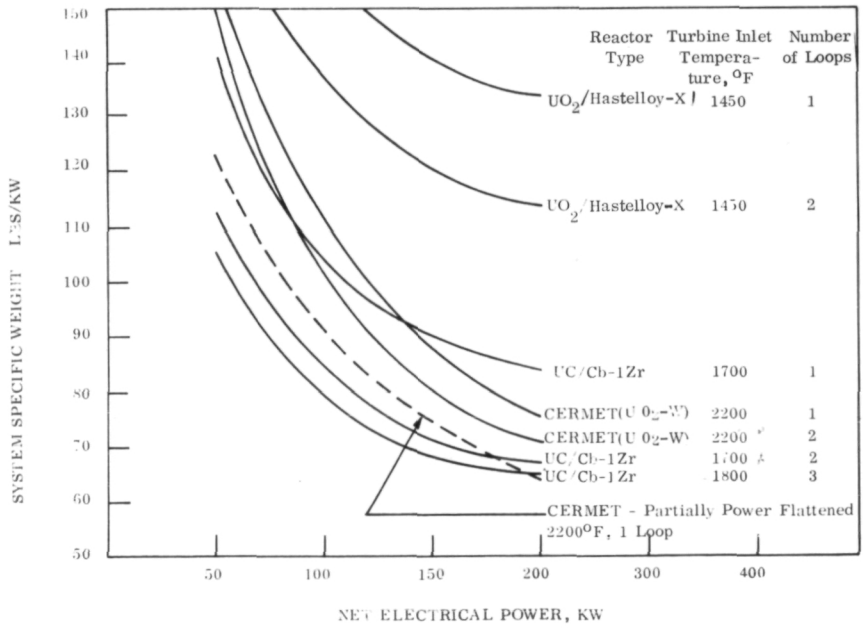

Figure 3-5. Specific Weight of Optimized Powerplants--Unmanned Application

*NASA CR-54397, July, 1965.

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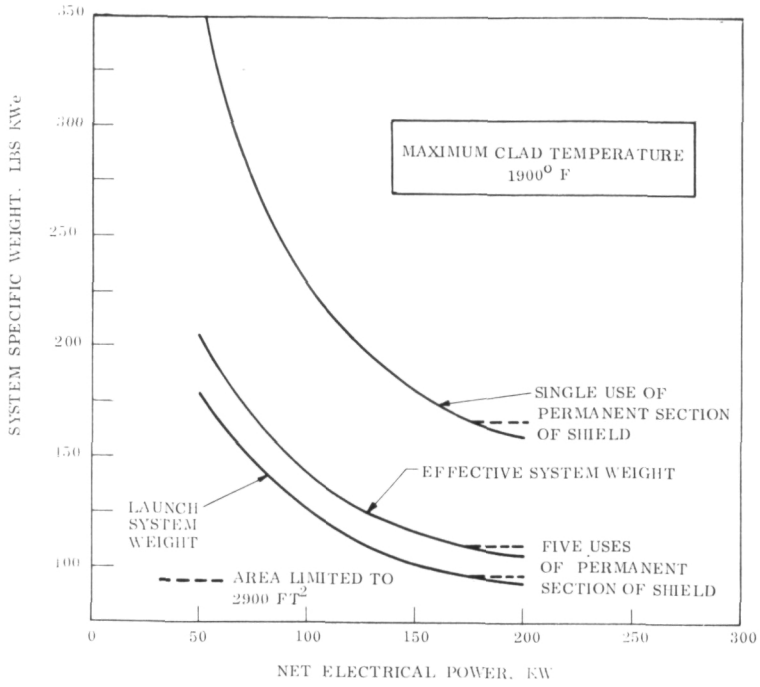

Figure 3-6. Summary of Performance of Brayton Cycle Powerplants For Use with Manned Space Station--Three Loop Systems, Dual Redundancy

(and hence weight). The savings in specific weight accompanying a change from a power flattened design to a uniform fuel loading design is greatest for the cermet core reactor, because it has the largest diameter of the three reactors considered.

The three-loop system is lighter than the two-loop system with the same reactor clad temperature because of the higher turbine inlet temperature possible with a separate liquid metal-to-gas heat exchanger. This heat exchanger need not be shielded from the payload and hence can be made large, with a high effectiveness, and with a lower pressure drop than can be achieved with a reactor heat source. This result of using a separate heat exchanger to achieve lower pressure and temperature drops also explains the cause of the weight savings with a separate radiator loop. In the radiator the chief seat of the savings is in the smaller tubes possible and the smaller total temperature and pressure drops achievable with a NaK filled radiator.

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The specific weight of three-loop systems with man-rated shields (25 REM/yr at the payload plane), including sufficient 4π shielding so that the dose to a typical ship rendezvousing with the station during powerplant operation is kept below 1 REM/rendezvous, is shown in Figure 3-6. Systems optimized for single and multiple uses of the permanent section of the shield are shown. The curves for five uses of the permanent section of the shield show both the launch specific weight of the replacement powerplant and the effective specific weight, which includes one-fifth of the weight of the permanent section of the shield. The specific weight of the initial launch of the system optimized for five uses of the permanent section of the shield, is slightly greater than that of the powerplant optimized for single use of the entire shield. This is because when multiple use is made of the majority of the shield it pays to decrease the primary heat exchanger pressure drop in order to decrease the radiator area and weight. This decrease in pressure drop results in an increase in shield weight which, when amortized over the multiple uses, is less than the weight savings due to reduction in radiator area.

3.3 RADIATOR STRUCTURAL MODEL

The weight added to the radiator for structural purposes is considered in two categories:

A. The weight of primary load carrying elements such as longitudinal stiffeners, stiffening frames, and additional web material.

B. The weight of parasitic items, not dependent on the load carrying requirement such as attachment frames for joints between bays, header supports, insulation, etc.

3.3.1 LOAD CARRYING ELEMENTS

The load carrying capability of a radiator can be determined by a structural analysis of the radiator considered as a shell under compressive and shear loading. The results of such an analysis are shown in Figure 3-7, summarized by plotting the parameters $d\bar{t}/R$ versus N_{xo}/R.

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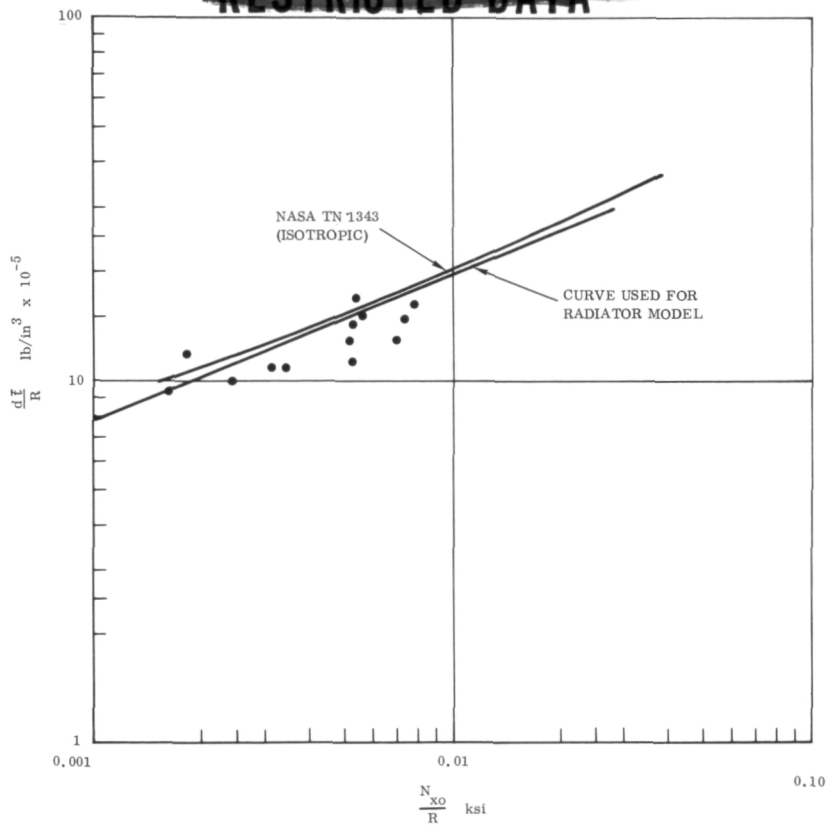

Figure 3-7. Radiator Structural Requirements

where d = density of material (lb/in^3)

$\bar{t}$ = effective thickness (in)

R = radius (in)

N_{xo} = equivalent axial loading

= $P_{eq}/2\pi R$ (lb/in)

Each point represents a radiator design for a Brayton cycle system; these points were obtained during preliminary design studies. Some scatter is observed because the points represent off-optimum designs and were obtained for both gas coolant systems and liquid metal coolant systems. For purposes of deriving a structural model, a conservative envelope to the points was selected by the equation

$$\frac{d\bar{t}}{R} = \left(\frac{N_{xo}}{R}\right)^{.4} \cdot 125 \cdot 10^{-5} \qquad (1)$$

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It is interesting to note that this equation agrees closely with the modified classical buckling equation derived by Batdorf, Schildcrout, and Stein* to fit test data of isotropic, thin-walled cylinders in axial compression.

To derive an expression for the loading index N_{XO}/R, the aerodynamic loading for various boosters is considered. For example, the loads at the booster interface for a Saturn V with an S-IVB upper stage are

$$P = 270,000 \text{ lb. (axial)}$$
$$M = 29 \times 10^6 \text{ in-lb. (bending moment)}$$

based on an Apollo payload. The loads may be combined to give an equivalent axial load

$$P_{eq} = P + \frac{4M}{D}$$

where D = diameter at booster interface.

If the bending moment is assumed to be proportional to the overall length of the payload, the equivalent axial load for any payload becomes

$$P_{eq} = 270 + 0.695\ L$$

where L = overall length (in)

P_{eq} = equivalent load at booster interface (KSI)

If the equivalent axial load is assumed to vary linearly from the tip of the payload (where it is zero) to the booster interface, the equivalent axial load at any distance x is

$$P_{eq} = (270 + 0.695\ L)\ \frac{x}{L}$$

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* Batdorf, S. B., Schildcrout, M., and Stein, M., "Critical Stress of Thin-Walled Cylinders in Axial Compression", NACA TN 1343, 1947.

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The loading index is

$$\frac{N_{xo}}{R} = \frac{P_{eq}}{2\pi R^2} = (270 + 0.695\ L)\ \frac{x}{2\pi R^2 L}$$

For the launch vehicles considered in this study, the assumed equivalent loading curves are as shown by Figure 3-8. It is noted that the curves do not decrease to zero at the forward end of the vehicle but maintain a minimum loading due to dynamic conditions. This value is attained by assuming a 30 g response to the dynamic input. With a concentrated mass of approximately 6000 lbs (reactor, shield, etc.) at the forward end of the vehicle, the minimum equivalent load is taken as 180 KSI.

The basis of the structural model is to compare the effective thickness of the radiator at each point along its length with the thickness necessary to satisfy the structural requirements. The weight of structure added is then the difference in effective thickness, integrated over the surface of the radiator.

3.3.2 PARASITIC WEIGHT

The major items of parasitic weight are associated with joints between bays of the radiator. These include attachment frames, header supports, pigtails, fasteners, separation devices to allow for differential expansion, stiffening for "kick loads" between cylindrical and conical bays, and reinforcement required because of load path eccentricities. Since, the number of bays is normally proportional to the radiator area it is possible to express the weight of all parasitic items, including those not related to joints between bays (such as insulation, coatings, tolerances), in terms of the radiator area. Based on a number of preliminary radiator designs, the parasitic weight of aluminum radiators in 0.15 lbs/ft^2.

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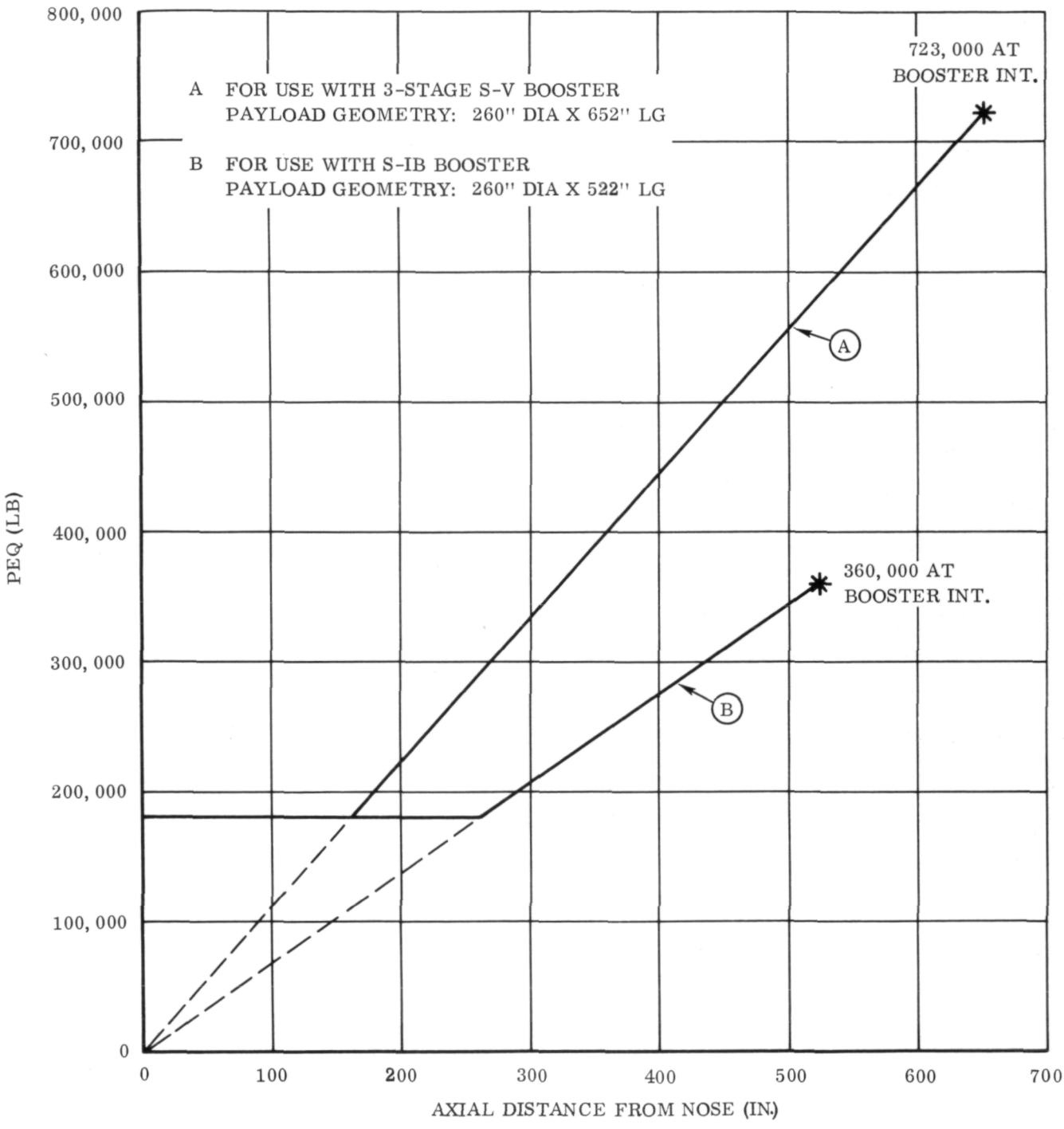

Figure 3-8. Assumed Equivalent Loading Curves

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3.4 AREA LIMIT MODEL

The radiator models developed for use in the Brayton Cycle System optimization programs are based on radiators of an unlimited area design. For a given system, however, the area available is generally not unlimited but is determined by the payload envelope of the intended launch vehicle. Within this limiting envelope, many configurations can be conceived which are advantageous to certain of the system components. On the unmanned vehicle, for example, a shallow cone angle substantially reduces the shield volume and consequently shield weight; it also reduces the available radiating surface which, for a specified power level, must be compensated by an increase in radiator fin efficiency, and/or increased operating temperatures and/or decreased pressure loss. The effect of these changes on the total system may more than offset the gain of reduced shield weight, hence the variation of radiator weight with area restrictions must be included.

Figure 3-9 illustrates a convenient form of describing the weight increase due to area limitations. The curve plots the dimensionless ratios of A/A_o and W/W_o, where A_o and W_o are the area and weight, respectively, of the area unlimited optimum radiator, and A and W refer to the restricted area design. A considerable amount of scatter is found for low values of A/A_o, i.e., fin efficiencies near unity. This is due to variation in the levels of operating temperatures and the weak sensitivity of fin efficiency to weight at high fin efficiencies. The resulting correlation used to describe the area limit effect is the solid line of Figure 3-9 and is given by the equation.

$$\frac{W}{W_o} = 0.99 + 0.1 \left[4^{(8.34 - 10\ (A/A_o))} \right]$$

3.4.1 MEAN TIME TO FAILURE MODEL

To describe the effects of increased meteoroid protection on radiator weight a "mean time to failure" model has been added to the existing radiator models. The two parameters describing the meteoroid protection, survival time and survival probability, are combined

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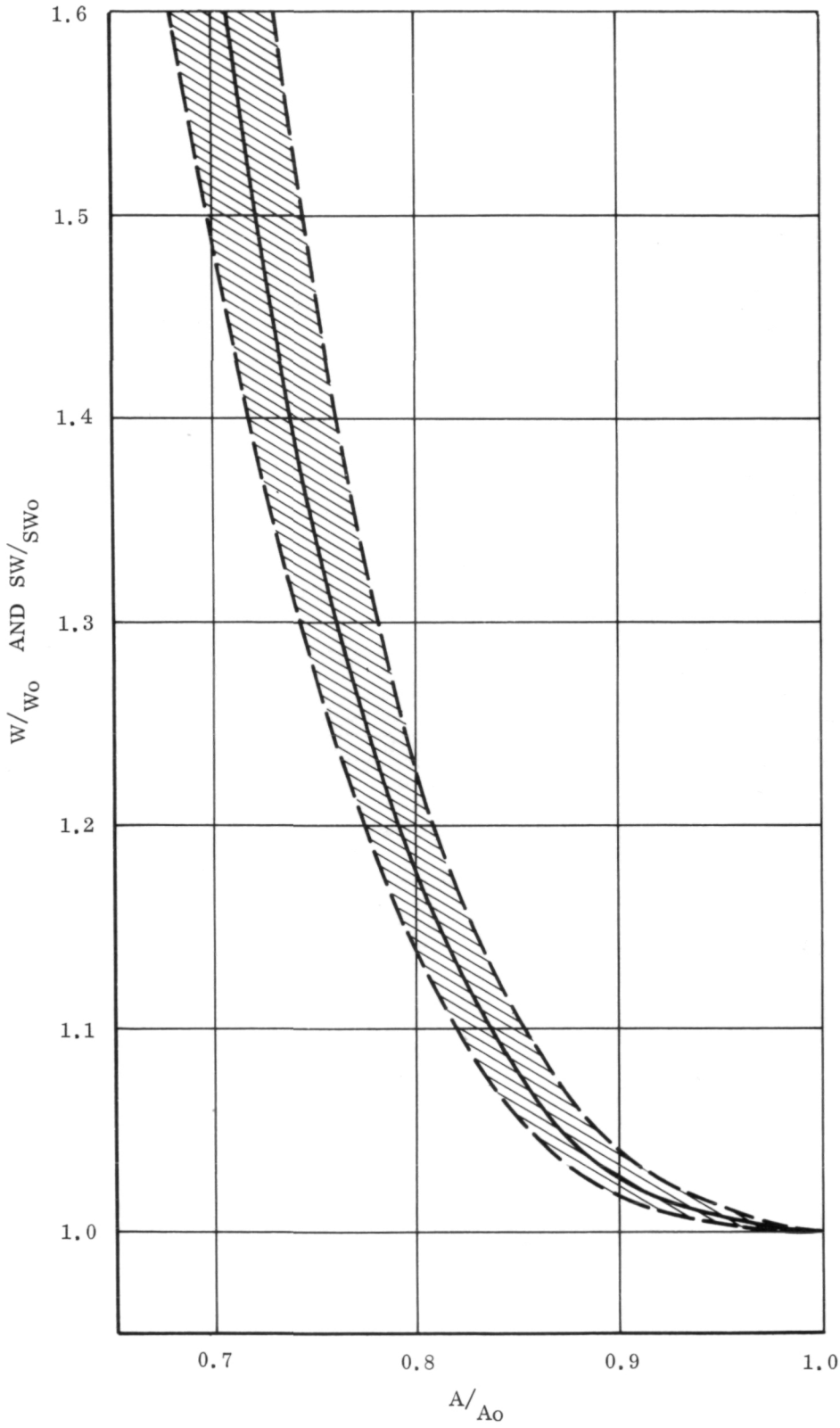

Figure 3-9. Weight Requirements for Area Limited Radiators

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to a single parameter termed mean time to failure. The relation of these quantities is given by

$$R = e^{-\tau/\theta}$$

where R = survival probability
T = survival time (hrs)
θ = mean time to failure (hrs)

Figure 3-10 graphically illustrates this relation. Figure 3-11 illustrates the radiator weight variation with mean time to failure and the curve is seen to be normalized to MTTF = 200,000 hrs. The equation describing this curve is

$$\frac{W}{W_o} = 0.2485\ (MTTF)^{0.1142}$$

where MTTF = mean time to failure (hrs)
W = radiator weight (lbs)
W_o = radiator weight at MTTF = 200,000 hrs (lbs)

3.5 STARTUP

The startup is achieved for a nuclear Brayton cycle by gas injection from a high pressure supply. The system is initially at low pressure and the blowdown procedure accelerates the turbocompressor and turboalternator. A dump valve is provided to insure restart ability. With large pressure ratios across the turbines they operate like open cycle components and large torques are available at zero and low speeds. Thus the system can accelerate rapidly. Typical turbomachinery startup times are estimated to be of the order of one minute or less.

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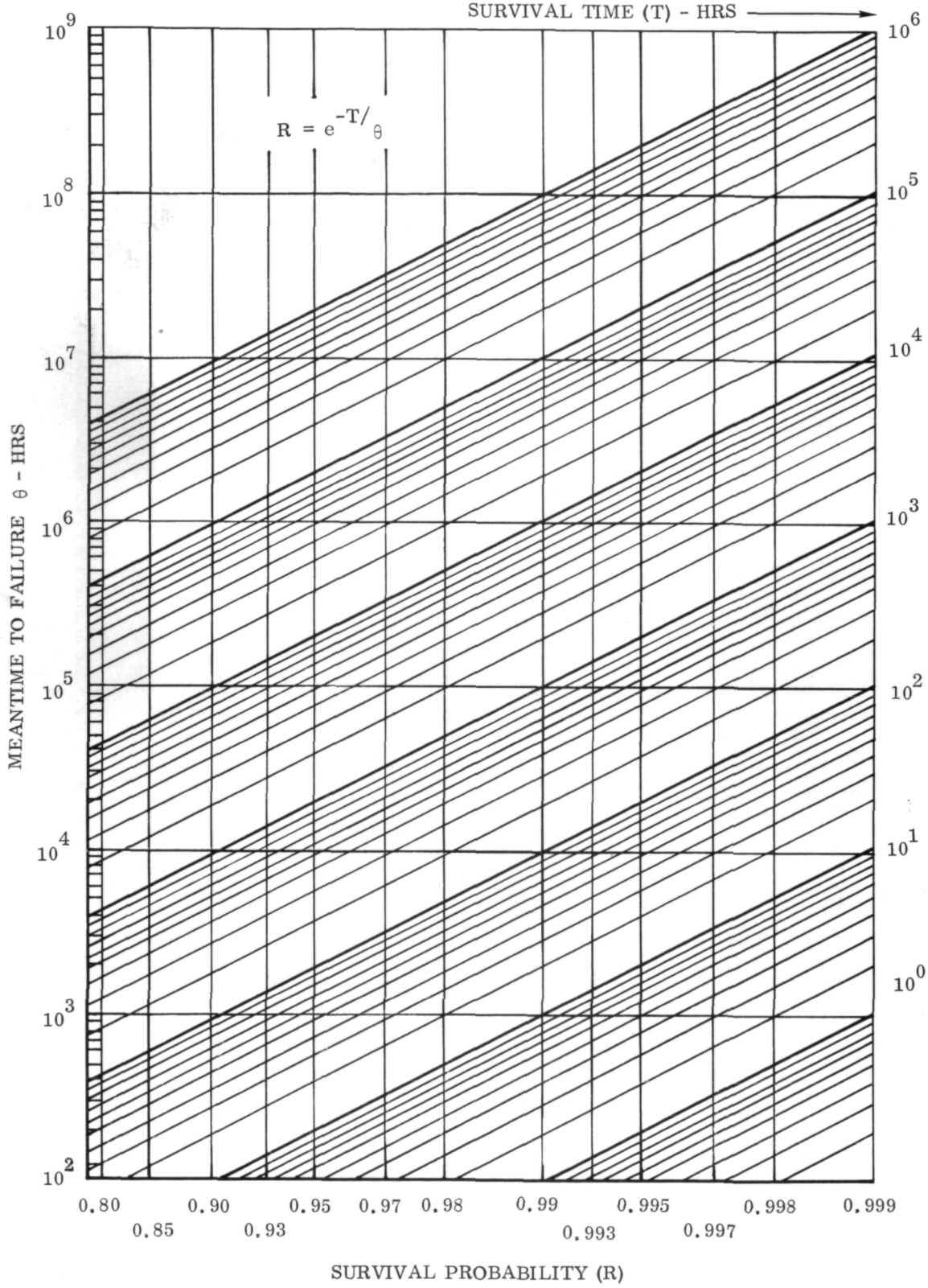

Figure 3-10. Mean Time to Failure Requirements

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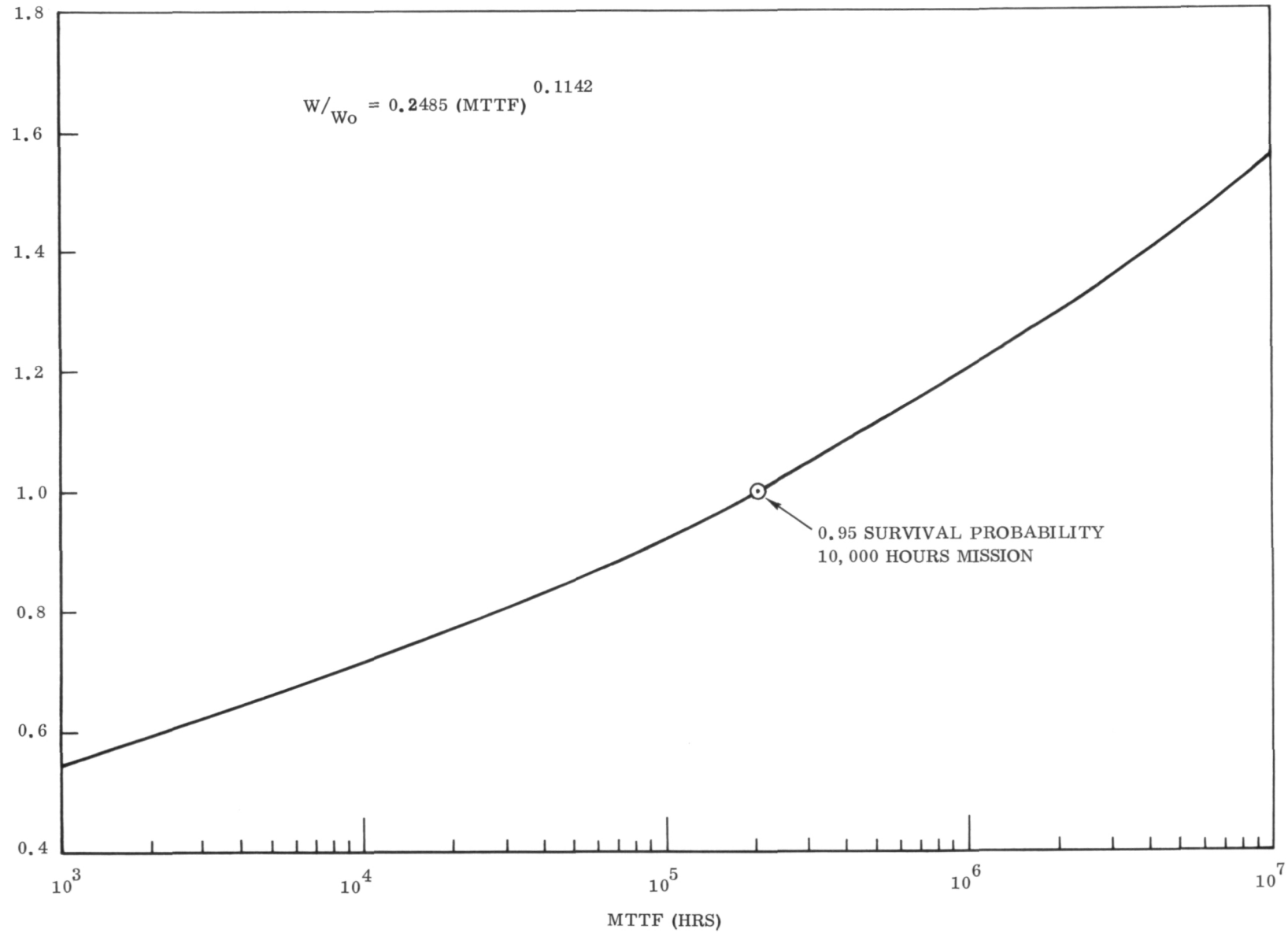

Figure 3-11. Effect of Mean Time to Failure on Radiator Weight

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The powerplant startup would commence with initiation of reactor startup at a low power level, about one percent of design power. When the reactor reaches operational temperature then the turbomachinery startup is initiated. Since no flow is in the reactor during its warm-up period, and the volumetric heat capacity of the gas is very low, the pressure level within the gas cooled reactor is immaterial. The primary loop of the liquid metal system reactor would start as reactor approached design temperature in order to heat up the primary heat exchanger. This requires auxiliary power.

The radiator of the one-loop system would initially be isothermal at a temperature considerably below the minimum design value. Thus the compressor inlet temperature would initially be low. The alternator and power control system would have to be capable of handling the excess power during the radiator warm-up period. Speed control of the turbocompressor is required. The flow in the liquid metal radiator in the three-loop system need not be started until the turbomachinery start is initiated, since the heat capacity of the radiator loop heat exchanger is sufficient to carry the system until the radiator loop circulation is accelerated.

A power dump control system is recommended in order that the turbomachinery and reactor may operate at fixed conditions. Thermal and stress cycling are among the prime causes of turbomachinery failure. Electrical control can easily be simulated for ground testing, and a clean interface is beneficial.

The gas storage provides a reservoir for restart and leak makeup. Dump valves for restart may leak up to 5 pounds per year; however, proper placement of the dump valve at a low temperature location permits this leakage to be minimized or avoided.

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4. CONCEPTUAL DESIGN OF A POWERPLANT FOR A MANNED SPACE STATION

A conceptual design of a Brayton cycle powerplant for use in supplying power for a manned orbiting spacecraft was prepared in order to determine the powerplant performance and spacecraft integration requirements. Previous work investigated the factors influencing the design of a nuclear powerplant for use with a manned orbiting space station.* The large three-spoke station with an arm-mounted powerplant was selected since previous work had already examined the application of mercury-Rankine powerplants for this mission. The major weight item is the shield, amounting to 45% of the total powerplant weight, while the radiator accounts for 26%. Therefore, because of the requirements of shielding for use on a manned space station, the powerplant optimization becomes focussed first on reduction of shield weight.

The liquid-metal cooled, Cb-1Zr clad, UC fueled reactor had the smallest core of those reactors considered. The use of liquid metal coolant eliminates the need for power flattening, resulting in a smaller core than could be made for a gas cooled reactor, and results in a higher turbine inlet temperature than can be obtained with a gas cooled core. The Nak-to-gas heat exchanger is very compact. An isolated primary loop is needed to prevent any fission fragment leakage induced radioactivity in the coolant from irradiating the payload. Systems studies have determined that the use of an additional radiator loop results in a savings in system weight since the reduction in the gas pressure drop in the heat exchanger can be made substantially smaller than that found in a gas-filled radiator; that the

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*Study on Application of Nuclear Electric Power to Manned Orbiting Space Stations

(a) Phase I, Feasibility Studies and Parametric Data, GE 63SD865, Dec. 20, 1963

(b) Phase II, Station/Powerplant Integration Studies, GE 64SD647, June 5, 1964

(c) SNAP-8 Reactor Support Data, Appendix A to (b) above, Classified C-RD, GE 64SD767, June 5, 1964

(d) Phase III, SNAP-8 Evaluation and Development Program Recommendations, GE 64SD914, and NASA CR-54160

(e) SNAP-8 Reactor Growth Potential, Appendix A to (d) above, Classified C-RD, GE 64SD945, Sept. 7, 1964

(f) Final Summary Report, GE 64SD913, and NASA CR-54161, Sept. 7, 1964

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boundary layer temperature drop is lower with the separate heat exchanger; and that the savings in radiator weight more than compensates for the additional heat exchanger, pumps, and liquid metal inventory. The three-loop approach results in the lightest weight system, besides offering the possibility of providing redundant complete power conversion loops. It was therefore selected for the application.

4.1 CONFIGURATION DESCRIPTION

The conceptual design of a Brayton cycle powerplant for use with a manned system is illustrated by Figure 4-1. The configuration presented is intended for use with the three-spoke space station shown in the inset of Figure 4-3. Since space station life is expected to be on the order of five years or more, and the powerplant design life is 10,000 hours, consideration must be given to removal and replacement of the powerplant. The powerplant studied is considered as a replacement module only, since it was found that the radiator area requirement for a 150 KWe powerplant was too large to permit a single design to be launched with the space station initially and then to be used, unaltered, as replacement units.

Total shield weight for the reference design is 12,520 pounds, of which 10,640 pounds is attributable to the large fixed segment which is permanently attached to the space station arm. Use of the Saturn 1B booster prohibits the launch of the powerplant with the total shield in place due to excessive bending moments induced at the booster interface. Bending moments would be reduced to an acceptable value by locating the permanent section of the shield so that its center of gravity is less than six feet above the booster interface during launch. The large segment of shield can be secured for launch in the lower portion of the central access tube. Six hundred pounds of structure is required to transmit the resulting launch loads to the booster adapter ring.

The central tube provides access by the crew for inspection and maintenance purposes. The tube seals against an extension of the space station arm. The volume within the radiator can even be pressurized and access is offered through the ports in the tube.

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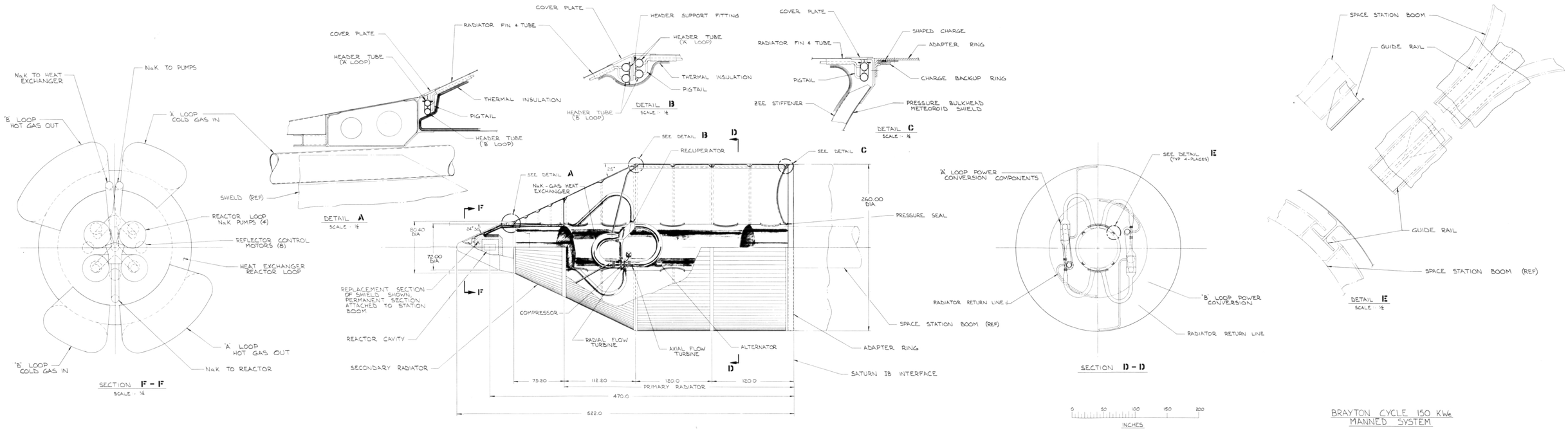

BRAYTON CYCLE 150 KWe
MANNED SYSTEM

Figure 4-1. Brayton Cycle 150 KWe Manned System

Inspection and maintenance capabilities are expected to contribute to overall system reliability. Two power conversion loops are provided so that power can be provided following a radiator puncture, or other type of catastrophic failure. Radiator studies have shown that, for this powerplant, when the weight of the additional feed and return lines, headers, pumps, and fluid inventory is considered, lighter systems result by designing the radiator for increased survival probability than by providing redundancy. The redundant power conversion loop is provided in order to increase the reliability of the complete powerplant. No reliability information is available on zero gravity, gas bearing, nuclear Brayton cycle power conversion systems. It is expected that such a system would be ground tested sufficiently so that an adequate level of confidence in a high reliability is demonstrated. However, provisions must be made for random failures. Redundant equipment is an excellent means of making such provision.

Figure 4-2 illustrates the radiation shield configuration and identifies the portion of the shield which remains attached to the station boom, and that is replaced with each powerplant. The shield contains lithium hydride for neutron absorption and tungsten for the gamma shielding. The tungsten is disposed in layers to absorb both primary and secondary gamma photons. Shield mass distribution is such that approximately 85% of the total weight can be attached permanently to the station. The smaller portion of the shield completely encloses the reactor and incorporates two NaK-gas heat exchangers around its outer surface. Gas lines from the power conversion equipment are routed around the fixed shield and enter the heat exchangers through the forward end; this arrangement provides a clean separation boundary and simplifies powerplant replacement techniques. The 1267^{o}F gas entering the primary heat exchanger is also used to cool the reactor pressure vessel and the replacement section of the shield. Shield cooling is required since the leakage power is about 10% of the reactor power. The first two attenuation lengths of shield absorb 85% of the leakage power. Figure 4-3 illustrates the sequential steps necessary for powerplant replacement.

The conceptual arrangement of the 150 KWe powerplant is shown in Figure 4-1. General configuration is of the cone-cylinder type; the 260-inch diameter cylindrical section is

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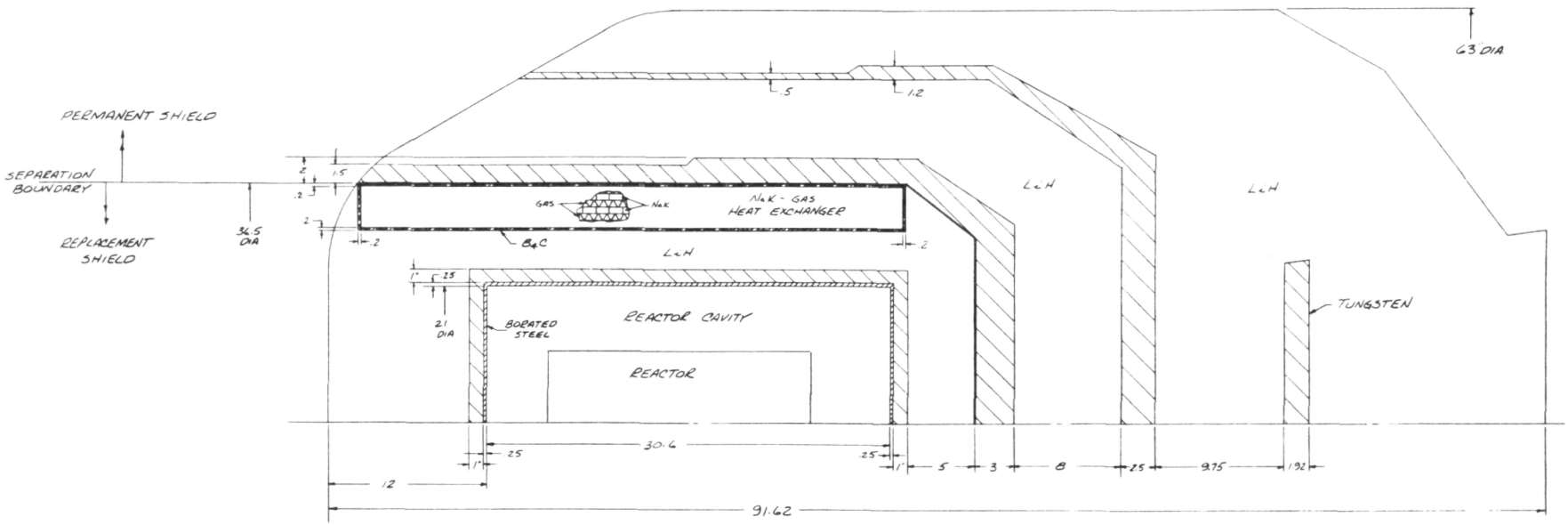

Figure 4-2. Radiator Shield Configuration

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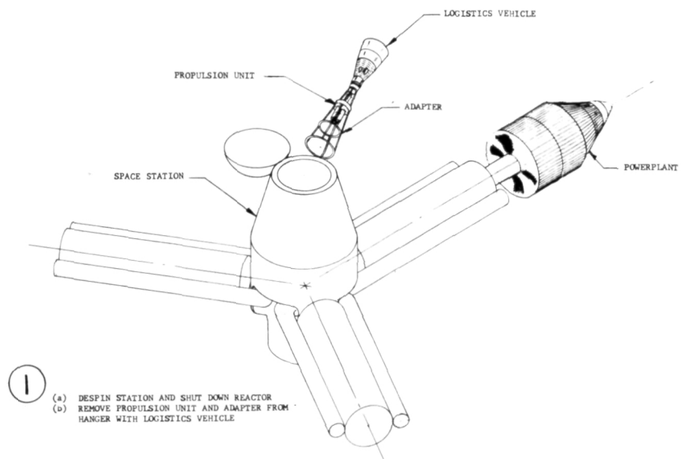
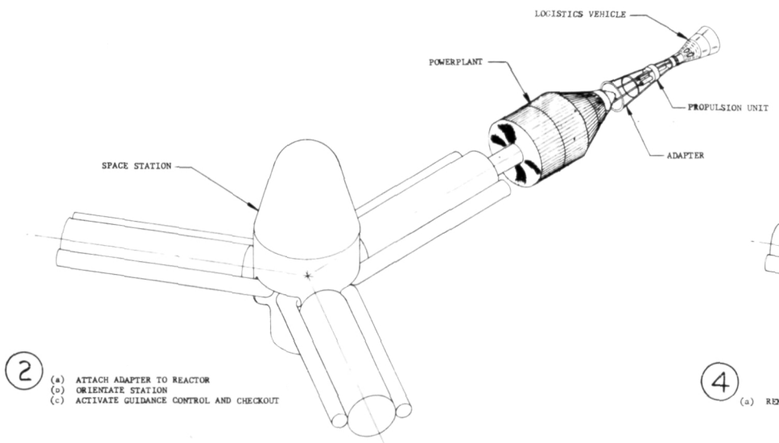
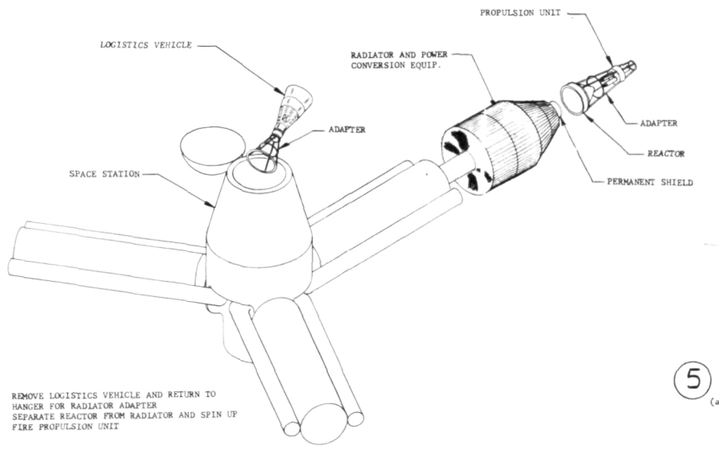


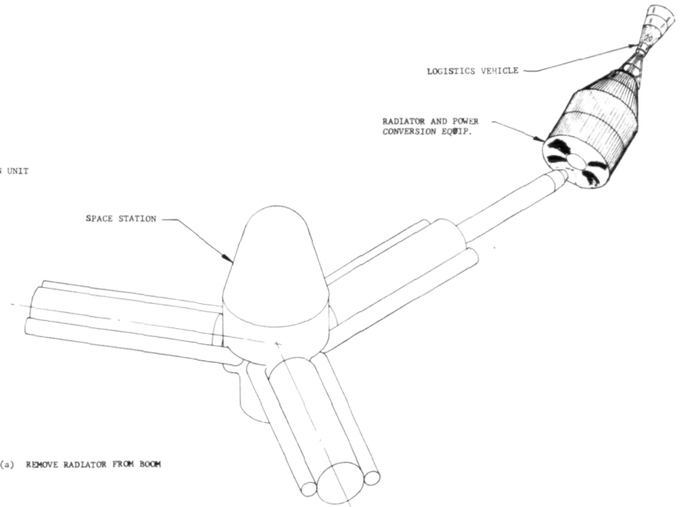
(1) (a) DESPIN STATION AND SHUT DOWN REACTOR
(b) REMOVE PROPULSION UNIT AND ADAPTER FROM HANGER WITH LOGISTICS VEHICLE



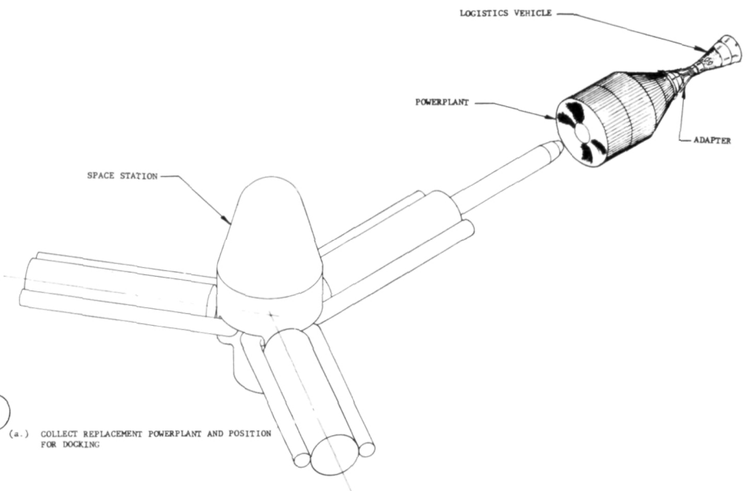
(2) (a) ATTACH ADAPTER TO REACTOR
(b) ORIENTATE STATION
(c) ACTIVATE GUIDANCE CONTROL AND CHECKOUT



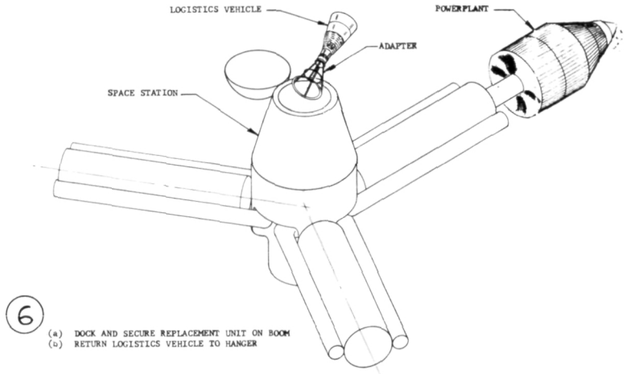
(3) (a) REMOVE LOGISTICS VEHICLE AND RETURN TO HANGER FOR RADIATOR ADAPTER
(b) SEPARATE REACTOR FROM RADIATOR AND SPIN UP
(c) FIRE PROPULSION UNIT



(4) (a) REMOVE RADIATOR FROM BOOM



(5) (a.) COLLECT REPLACEMENT POWERPLANT AND POSITION FOR DOCKING



(6) (a) DOCK AND SECURE REPLACEMENT UNIT ON BOOM
(b) RETURN LOGISTICS VEHICLE TO HANGER

Figure 4-3. Powerplant Disposal Technique

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capped with a 25° cone. Overall length, including the booster adapter ring, is 43.5 feet, the envelope limit of the S1B booster.

Only one liquid metal reactor was considered. The core employs uranium carbide, refractory metal clad, pin-type fuel elements with a maximum clad temperature of 1900°F. The compact size of this reactor effects sustantial savings in shield weight. As shown in Figure 4-1, the reactor/shield assembly is located at the extreme end of the conical section; this is the optimum location from the standpoint of shield weight economy. Section F-F shows details of the piping arrangement at the forward end of the reactor. Reactor loop NaK pumps are mounted at the forward end of the shield to minimize radiation to the space station. Gas lines to the reactor heat exchanger are flattened in cross-section in the vicinity of the shield. Dimensions of the flattened gas lines are such as to provide a hydraulic diameter equal to the circular piping in the remainder of the power conversion system.

The primary powerplant radiators occupy the entire cylindrical surface area and the lower bay on the conical section. Total surface area of the primary radiators is 1925 ft^2. The upper bay on the conical section is a 225 ft^2 secondary radiator which provides cooling capability for the alternators, control drives, and bearings. The thermal load for the secondary radiator is estimated at 40 KW. To insure a high degree of reliability, two complete power conversion systems are incorporated in the design. This redundancy concept is maintained in the radiator design to the extent that two complete fluid networks are provided for each radiator function. Each of the fluid circuits in the primary radiator has a survival probability of 0.95 for 10,000 hours while the secondary radiator loops are designed for a 0.98 survival probability for 10,000 hours. The combined survival probabilities for the total primary system is 0.975 for 10,000 hours; the combined survival probability for the total secondary system is 0.99 for 10,000 hours. Detail B of Figure 4-1 shows header arrangements used for the shared fin systems.

The effect of survival probability for 10,000 hours, or mean time to failure on system specific weight is shown in Figure 4-4. Initial and replacement launch specific weights

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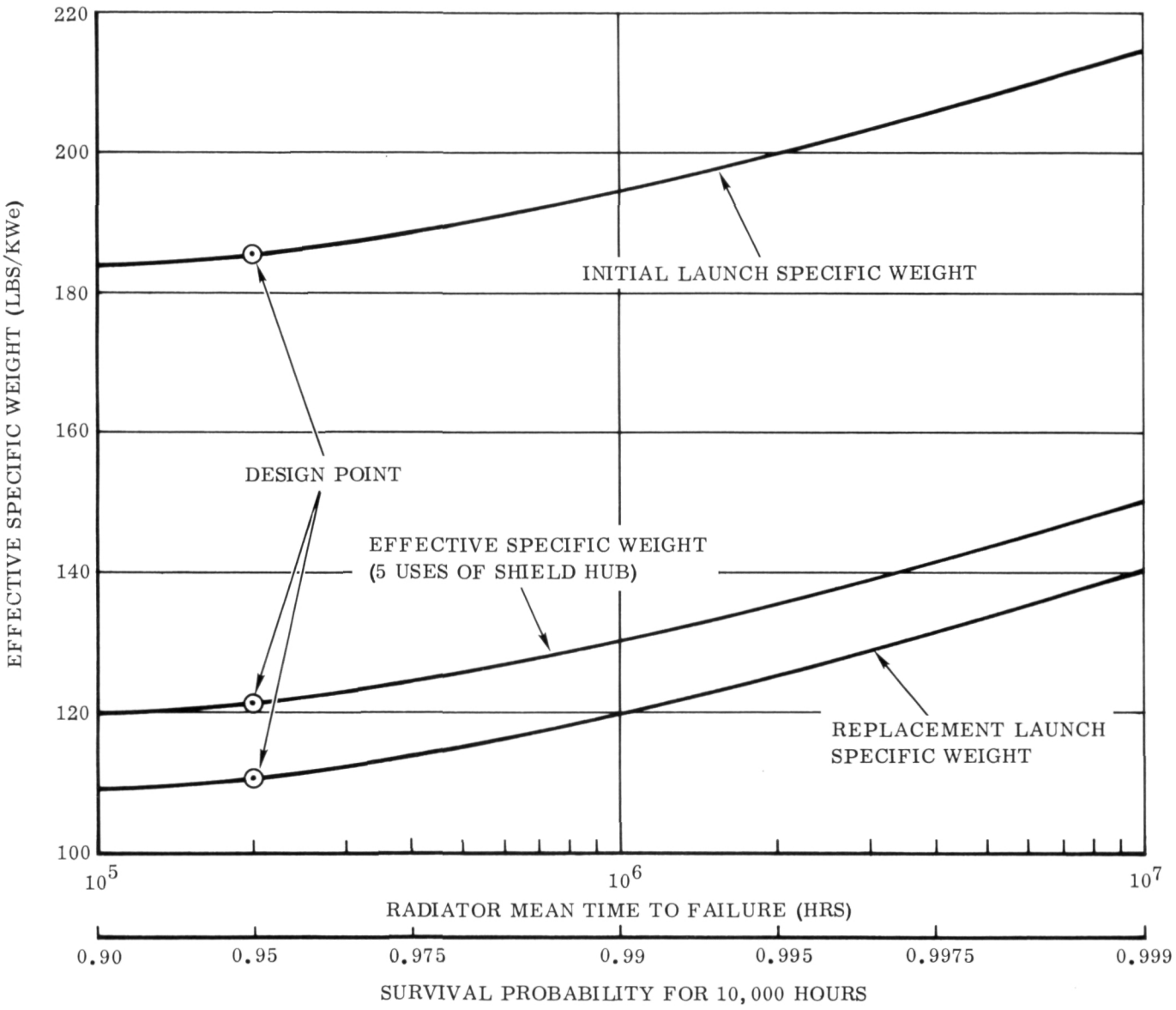

Figure 4-4. Effect of Survival Probability on Powerplant Specific Weight

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are shown as well as an effective system specific weight based on 5 uses of the permanent section of the shield. Increase in survival probability for 10,000 hours from 0.95 to 0.975 (halving the puncture probability) results in a weight penalty of 3 lbs/KWe, while decreasing the survival probability to 0.90 (doubling the probability of a puncture) only results in a savings of 1 lb/KWe.

The radiators and the concave pressure bulkhead form the exterior boundary for the pressurized power conversion compartment. A circular seal at the base of the tubular support column mates with the station boom to fully enclose the pressurized volume. This arrangement provides a continuous pressurized environment from within the space station to the power conversion compartment.

General arrangement of the two power conversion units and their associated piping is illustrated in Figure 4-1. Section D-D shows their mounting locations on either side of the tubular support column. The two power units are identical and consist of a radial flow turbo-compressor on one shaft followed in line by a second shaft with an axial flow turbo-alternator. The exhaust gas stream makes a right angle bend leaving the axial turbine; in this way, the alternator is sealed into the gas environment but occupies a dead-end corner. The turbo-machinery is based on solar Brayton cycle equipment under development by NASA.

Table 4-1 provides a detailed listing of design parameters for the 150 KWe Manned System, including specifications, temperatures and weights. Table 4-2 lists a weight summary tabulation for the replacement powerplant.

4.2 SYSTEM WEIGHT VARIATION WITH RADIATOR AREA

Variations of total system weight with primary radiator area for the 150 KWe manned system are given by Figures 4-5, 4-6 and 4-7. The four curves presented show the effect of minimum reactor core diameter. Comparison with analogous curves for 200 KWe unmanned system (Figures 5-4 and 5-6) shows the manned system to have a less distinct optimum

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Table 4-1. Design Parameters for 150 KWe Manned System

Optimized Parameters	Reactor Core Diameter	IN	9.5
	Pressure Loss Ratio in Reactor Loop HX	%	1.40
	Effectiveness of Reactor Loop HX	%	88
	Turbine Pressure Ratio	—	1.812
	Compressor Discharge Temperature	^{o}F	648
	Recuperator Pressure Loss Ratio	%	0.43
	Recuperator Effectiveness	%	87.0
	Pressure Loss Ratio in Radiator Loop HX	%	0.88
	Effectiveness of Radiator Loop HX	%	90
	Coolant Temp Rise in Reactor Loop	^{o}F	37
	Interconnecting Pipe Diameter	IN	5.5
Fixed Input Parameters	Electrical Power Output	KWe	150
	Working Fluid	—	NEON
	Compressor Efficiency	%	80.
	Turbine Efficiency	%	86.91
	Alternator Efficiency	%	88.
	Compressor Discharge Pressure	PSIA	260
	Reactor Maximum Clad Temperature	^{o}F	1900
	Reactor Minimum Core Diameter	IN	9.5
	Refector Thickness	IN	10.0
	Recuperator & HX Material	—	NICKEL
	Sink Temperature	^{o}F	-10
	Available Primary Radiator	FT^2	1925
	Radiator Mean Time to Failure	HRS	200,000
	Shield Materials	—	LiH/W
	Mission Time	HRS	10,000
Dependent Parameters	Turbine Discharge Temperature	^{o}F	1360
	Gas Inlet Temp to Radiator Side HX	^{o}F	741
	Compressor Inlet Temperature	^{o}F	352
	Gas Inlet Temp to Reactor Side HX	^{o}F	1267
	Turbine Inlet Temperature	^{o}F	1770
	NaK Temp at Reactor Inlet	^{o}F	1836
	NaK Temp at Reactor Outlet	^{o}F	1873
	NaK Temp at Radiator Inlet	^{o}F	700
	NaK Temp at Radiator Outlet	^{o}F	312
	Compressor Pressure Ratio	—	1.895
	Reactor Weight	LBS	1124
	Reactor Thermal Power	KW	784
	Overall Reactor Diameter	IN	19.5
	Radiator Thermal Load	KW	577
	Effective Radiating Temperature	^{o}F	468
	Primary Radiator Area	FT^2	1925
	Total Primary Radiator Weight (Incl. Structure)	LBS	7273
	Primary Radiator Parasitic Structure Wt.	LBS	288
	Primary Radiator Load Bearing Struct. Wt.	LBS	55
	*Recuperator Weight	LBS	585
	*Reactor Loop HX Weight	LBS	159
	*Radiator Loop HX Weight	LBS	393
	*Interconnecting Pipe Weight	LBS	341
	Total Shield Weight	LBS	12520
	Replacement Shield Weight	LBS	1880
	Secondary Radiator Weight	LBS	500
	Pressure Loss Ratio in Piping	%	1.06
	Mass Flow Rate	LBS/HR	20643
	Cycle Efficiency	%	22.8
	*Turbo-Machinery & Alternator Weight	LBS	725
	Spacecraft Integration Attachments	LBS	1380
	Total Weight of Replacement Powerplant	LBS	16563
	**Total Weight of Initial Powerplant	LBS	27803
	Specific Weight of Replacement Powerplant	LBS/KWe	110.4
	**Specific Weight of Initial Powerplant	LBS/KWe	185.3

* Weight shown applies to one power conversion system
** Weight includes 600 lbs additional structure for support of permanent shield

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Table 4-2. Weight Summary for 150 KWe Replacement Powerplant

Powerplant			13303 lbs
Reactor		1124	
Turbomachinery	Total for two 150 KWe units	700	
Alternator		750	
Recuperator		1170	
Reactor HX		318	
Radiator HX		786	
Piping		682	
Primary Radiator Matrix & Feeds		6930	
Primary Radiator Structure		343	
Secondary Radiator Matrix & Feeds		491	
Secondary Radiator Structure		9	
Shield (Replacement Portion Only)			1880 lbs
Spacecraft			1380 lbs
Aerodynamic Fairing		225	
Booster Adapter		250	
Pressure Bulkhead		275	
Insulation		100	
Center Support Tube		530	
Launch Weight			16563 lbs

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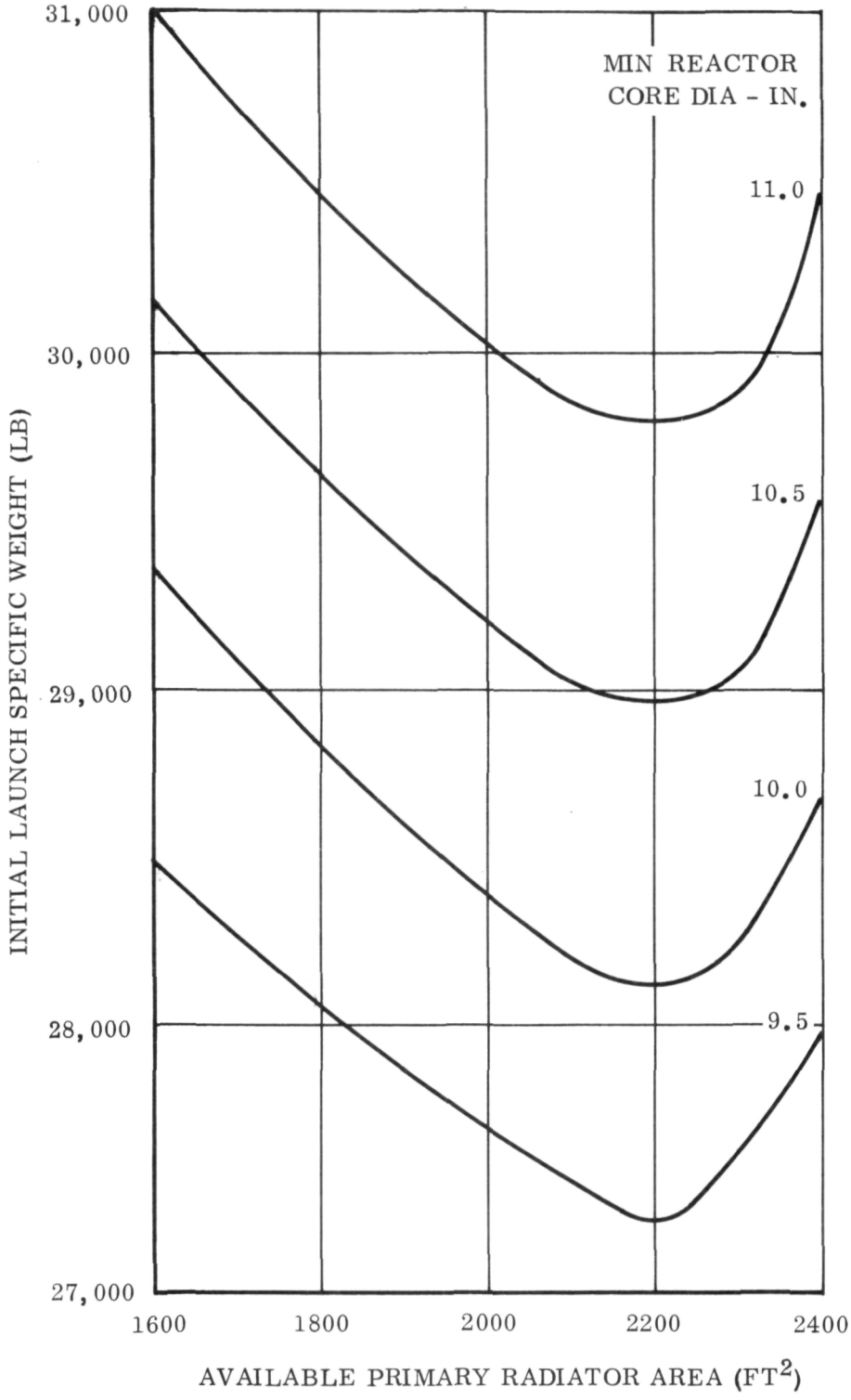

Figure 4-5. Variation of Initial Launch Specific Weight with Primary Radiator Area

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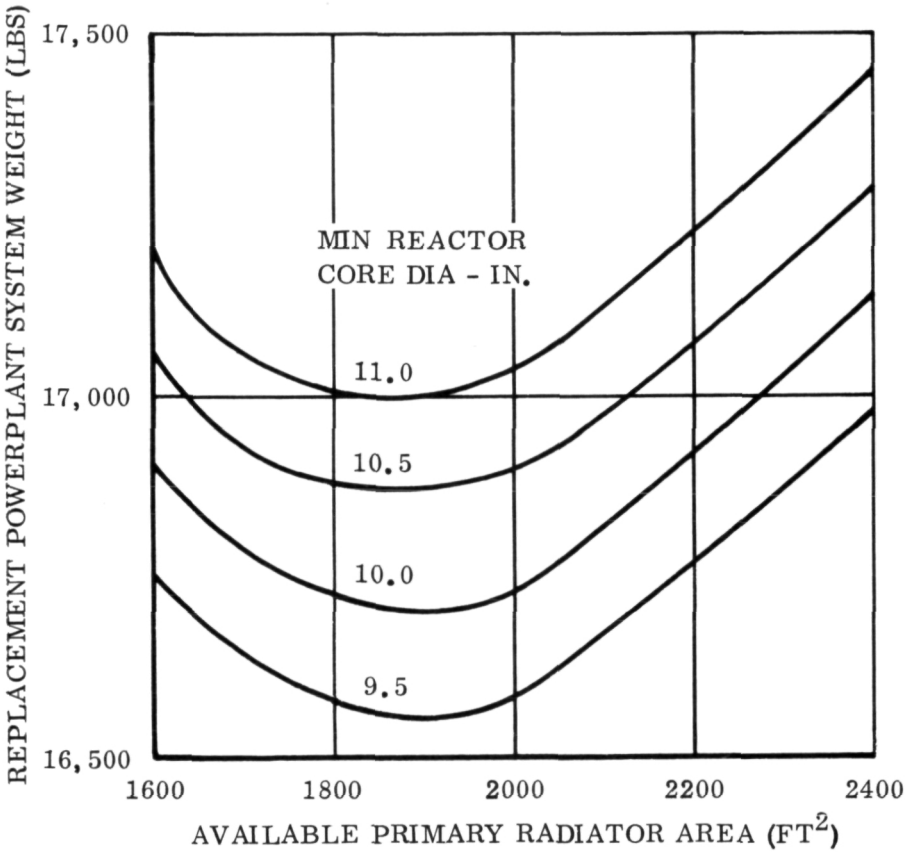

Figure 4-6. Variation of Replacement Powerplant System Weight with Primary Radiator Area

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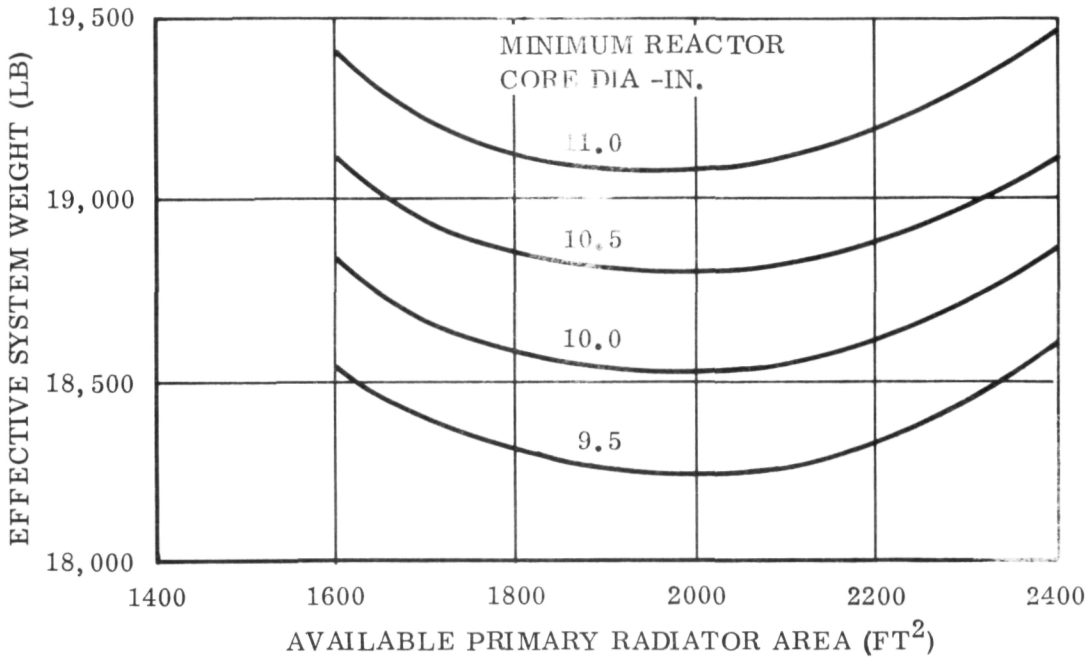

Figure 4-7. Variation of Effective System Weight with Primary Radiator Area

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point. Area limits from 1800 ft^2 to 2200 ft^2 yield system specific weights within 2% of the minimum attainable value. This relative independence of radiator area results from the fact that the manned system employs a 4π radiation shield, hence, shield weight is independent of the radiator cone angle.

Figure 4-8 shows the variation of radiator weight with area limit. The radiator system used for the manned application is one of the "shared fin" concept. This arrangement provides two complete and independent fluid networks placed on a common fin. Armor thicknesses are sized to provide a mean time to failure of 200,000 hours (0.95 probability of survival for 10,000 hours). The resulting matrix density of this type radiator is comparitively high — approximately 160% of the type used for the unmanned system. Tending to offset this is the elimination of the need for addition load bearing structure.

Considering the payload envelope limitations of the S-IB booster, and allowing 225 ft^2 for the secondary radiators, a cone-cylinder configuration with a 25^o cone half angle was selected for the conceptual design. This arrangement provides 1925 ft^2 for the powerplant radiators.

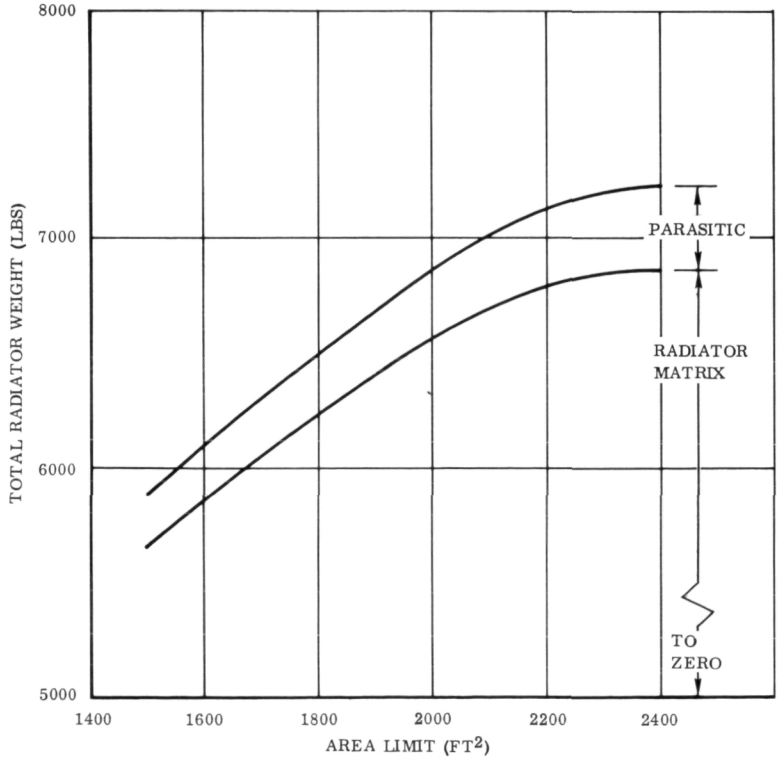

Figure 4-8. Variation of Radiator Weight with Area Limit

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4.3 RADIATOR DESIGN

The primary radiator system used for the manned system provides two complete fluid circuits, each capable of rejecting the thermal load required for full power operation. Since the redundant power conversion systems are not operated simultaneously, the two fluid loops share a common fin surface. Meteoroid protection is sized to provide a survival probability of 0.95 for 10,000 hours for each loop thereby giving the powerplant radiator system a survival probability of 0.975 for 10,000 hours.

Preliminary radiator designs obtained from the cycle optimization program are further refined using the Spartan radiator design program. A summary of the radiator parameters for the thermally optimized radiators is given in Table 4-3.

Secondary radiators for the 150 KWe power system also use the shared fin concept. Thermal load for this system is estimated at 40 KWe and an area of 225 ft^2 is provided. Each loop of the secondary radiator is designed with a survival probability of 0.98 for 10,000 hours or 0.99 for 10,000 hours for the complete secondary system.

Results of the structural analysis of the primary and secondary radiators are summarized by Table 4-4. Due to the high matrix density associated with this type of radiator, positive margins of safety for all failure modes result with only modest additions of load-carrying structure.

4.4 RECUPERATOR AND HEAT EXCHANGER DESIGN

Recuperators for the 150 KWe system are sized to satisfy the requirements determined by the cycle optimization program and are of the same type illustrated by Figure 5-10. Details of the optimized design are given in Table 4-5.

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Table 4-3. Summary of Radiator Parameters for 150 KWe Manned System

		Primary Radiator			Secondary Radiator
		Conical Bay	Upper Cylindrical Bay	Lower Cylindrical Bay	
Heat Rejected	KW	171	203	203	40
Area	FT^2	570	680	680	225
No. of Panels	—	2	2	2	2
Header Length	FT	27.1	34.0	34.0	15.1
Fluid Inlet Temp	°F	700	700	700	400
Fluid Outlet Temp	°F	312	312	312	374
*Tube Spacing	IN	3.2	3.3	3.3	4.3
Fin Thickness	IN	0.080	0.090	0.090	0.040
Tube Inside Dia.	IN	0.18	0.18	0.18	0.18
Feed Line Diameters	IN	← (1.1, 1.55, 1.91) →			1.2
Weight of Fins	LBS	636	852	852	126
*Weight of Tubes	LBS	632	653	653	122
*Weight of Headers	LBS	70	102	102	22
*Weight of Feeds	LBS	← (82 lbs total for each loop) →			38
Weight of 1 Loop Radiator	LBS	1338	1607	1607	309
Weight of 2 Loop Radiator	LBS	2042	2362	2362	491
Pressure Drop in Feeds	PSI	← (3.97 PSI Total) →			5.2
Pressure Drop in Tubes & Headers	PSI	0.18	0.18	0.18	2.2
Hydraulic Pump Work	KW	←	(0.11 Total)	→	0.07
*Mean Time to Failure	HRS	200,000	200,000	200,000	500,000
Coolant	—	NaK	NaK	NaK	ET-378
Coolant Flow Rate	LBS/HR	70660	83240	83240	12351
Sink Temperature	°F	-10	-10	-10	-10

* These values apply to one fluid network

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Table 4-4. Results of Structural Analysis of 150 KWe Manned System Radiators

	Units	Primary Radiator			Secondary Radiator
		Upper Bay	Center Bay	Lower Bay	
Equivalent Load (Top)	KSI	180	195	275	180
Equivalent Load (Bottom)	KSI	195	275	360	180
Tube Length	FT	10.36	9.825	9.825	7.38
Tube Spacing	IN	0.133	0.139	0.139	0.180
Fin Thickness	IN	0.080	0.090	0.090	0.040
RF (See Fig. 5-9)	IN	0.432	0.425	0.425	0.308
TAT (See Fig. 5-9)	IN	0.107	0.0939	0.0939	0.0775
TLT (See Fig. 5-9)	IN	0.015	0.015	0.015	0.015
Bay Diameter (Top)	IN	154	260	260	77
Bay Diameter (Bottom)	IN	260	260	260	154
Tapered Fins	—	No	No	No	No
Tube Stiffener Height	IN	0	0	0	0
Tube Stiffener Width	IN	0	0	0	0
Weight of Tube Stiffeners	LBS	0	0	0	0
No. of Rings Added	—	1	1	1	3
Height of Ring Added	IN	1.26	1.66	1.84	1.23
Weight of Rings Added	LBS	11.04	20.58	23.54	8.88
Margin of Safety for Panel Instability	—	0.497	0.550	0.136	0.745
Margin of Safety for Local Instability (Top)	—	248.0	136.1	96.24	6.82
Margin of Safety for Local Instability (Center)	—	110.1	112.8	83.23	2.18
Margin of Safety for Local Instability (Bottom)	—	63.4	96.24	73.28	0.862
Margin of Safety for General Instability (Top)	—	4.86	2.28	1.52	0.666
Margin of Safety for General Instability (Center)	—	4.09	1.72	1.18	0.430
Margin of Safety for General Instability (Bottom)	—	3.56	1.33	0.926	0.318

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Table 4-5. Summary of 150 KWe Manned System Recuperator Design

Recuperator Material	—	Nickel
Gas	—	Neon
Mass Flow Rate	LBS/HR	20643
Inlet Pressure (Side 1)	PSIA	143
Inlet Pressure (Side 2)	PSIA	260
Inlet Temperature (Side 1)	^{o}F	1360
Inlet Temperature (Side 2)	^{o}F	648
Outlet Temperature (Side 1)	^{o}F	738
Outlet Temperature (Side 2)	^{o}F	1270
Plate Thickness	IN	0.006
Fin Thickness	IN	0.004
Shell Thickness	IN	0.006
Plate Spacing (Side 1)	IN	0.402
Plate Spacing (Side 2)	IN	0.277
Fin Spacing (Side 1)	IN	0.040
Fin Spacing (Side 2)	IN	0.50
Core Length	FT	1.37
Core Width	FT	0.87
Core Height	FT	3.73
Heat Transfer Coefficient	$\frac{BTU}{HR\text{-}FT^2\text{-}^{o}F}$	228
Effectiveness	%	873
Pressure Loss Ratio (Each Side)	%	0.43
Core Weight	LBS	356
Manifold & Shell Weight	LBS	229
Total Weight	LBS	585

The gas-NaK heat exchangers for use with the three-loop system are counter flow designs similar in construction to the counter flow plate-fin recuperators used in this study. Detailed designs are accomplished with the aid of a computer program which satisfies the requirements for effectiveness and pressure loss ratio on the gas side and trades off the pumping requirements on the liquid side against heat exchanger weight. In the designs presented, the liquid side pumping requirements are related to the total system weight by a factor of 300 $lbs/KW_{hydraulic}$. Table 4-6 summarizes the details of the heat exchanger designs.

4.5 SENSITIVITY TO OFF-OPTIMUM OPERATION

The performance of the powerplant using other than optimum component specifications is shown in Figures 4-9 through 4-21. Each figure shows the initial and replacement launch specific weight and an effective specific weight based on the amortizing of the permanent section of the shield and its support over five launches. The sensitivity to increases in reactor diameter is shown in Figure 4-9. Increase in reactor diameter could arise from additions required for the reflectors, pressure shell, or the core itself. The initial specific weight is more sensitive to reactor diameter than the other curves because the effect of increased reactor size is to increase the shield weight. The lower fractions of the shield weight which is contained in the replacement system results in lower sensitivity to reactor diameter.

The sensitivity to primary heat exchanger fractional pressure drop and effectiveness are shown in Figures 4-10 and 4-11. This heat exchanger is small, since the NaK is an excellent heat transfer fluid and the NaK temperature change in the primary loop is considerably less than that of the gas. The large temperature differences in most of the heat exchanger result in a compact design.

The sensitivity to turbine pressure ratio shown in Figure 4-12 is moderate. Small changes, of 1%, in system specific weight, result from turbine pressure ratios in the range between 1.65 and 1.95. Because of the small sensitivity to pressure ratio it appears that it should

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Table 4-6. Summary of NaK-Gas Heat Exchanger Designs

	Units	Reactor Side HX	Radiator Side HX
Heat Exchanger Material	—	Nickel	Nickel
Fluid on Side 1	—	NaK	Neon
Fluid on Side 2	—	Neon	NaK
Mass Flow Rate (Side 1)	LBS/HR	315198	20643
Mass Flow Rate (Side 2)	LBS/HR	20643	237140
Inlet Pressure (Gas Side)	PSIA	255	140
Inlet Temperature (Side 1)	^{o}F	1873	741
Inlet Temperature (Side 2)	^{o}F	1267	312
Outlet Temperature (Side 1)	^{o}F	1836	352
Outlet Temperature (Side 2)	^{o}F	1770	700
Plate Thickness	IN	0.006	0.006
Fin Thickness	IN	0.004	0.004
Shell Thickness	IN	0.006	0.006
Fin Length	IN	0.50	0.50
Plate Spacing (Side 1)	IN	0.20	0.12
Plate Spacing (Side 2)	IN	0.145	0.20
Fin Spacing (Side 1)	IN	0.40	0.06
Fin Spacing (Side 2)	IN	0.072	0.40
Core Length	FT	0.95	2.79
Core Width	FT	2.0	0.50
Core Height	FT	0.42	3.36
Heat Transfer Coefficient	$\frac{BTU}{HR\text{-}FT^2\text{-}^{o}F}$	225	135
Effectiveness	%	88	90
Pressure Loss Ratio on Gas Side	%	1.40	0.87
Pressure Drop on Liquid Side	PSI	0.31	0.1
Hydraulic Pump Power on Liquid Side	KW	0.133	0.04
Core Weight	LBS	51	325
Manifold & Shell Weight	LBS	108	68
Total Weight	LBS	159	393

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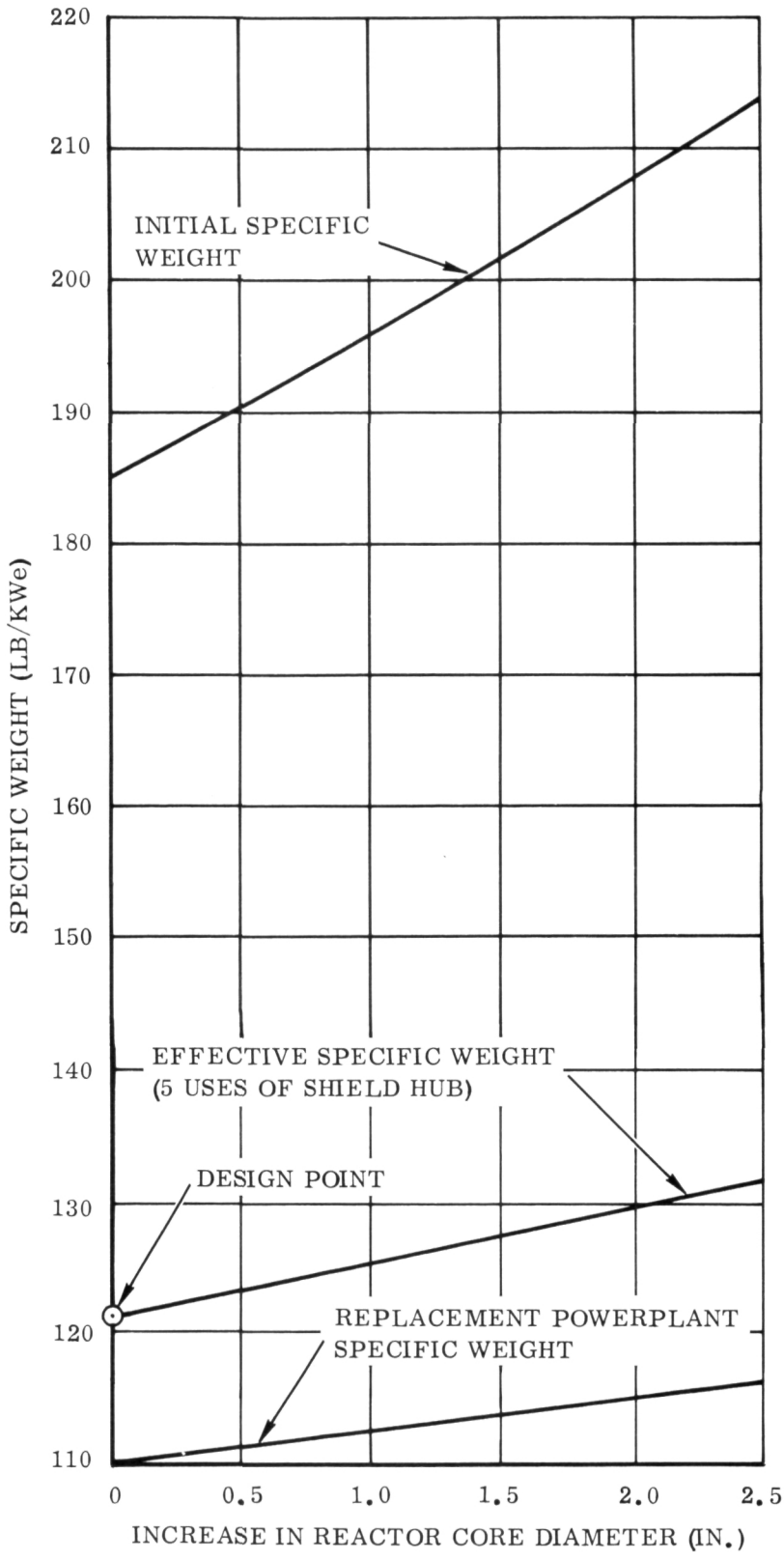

Fig. 4-9 Variation of Specific Weight with Increase in Reactor Core Diameter

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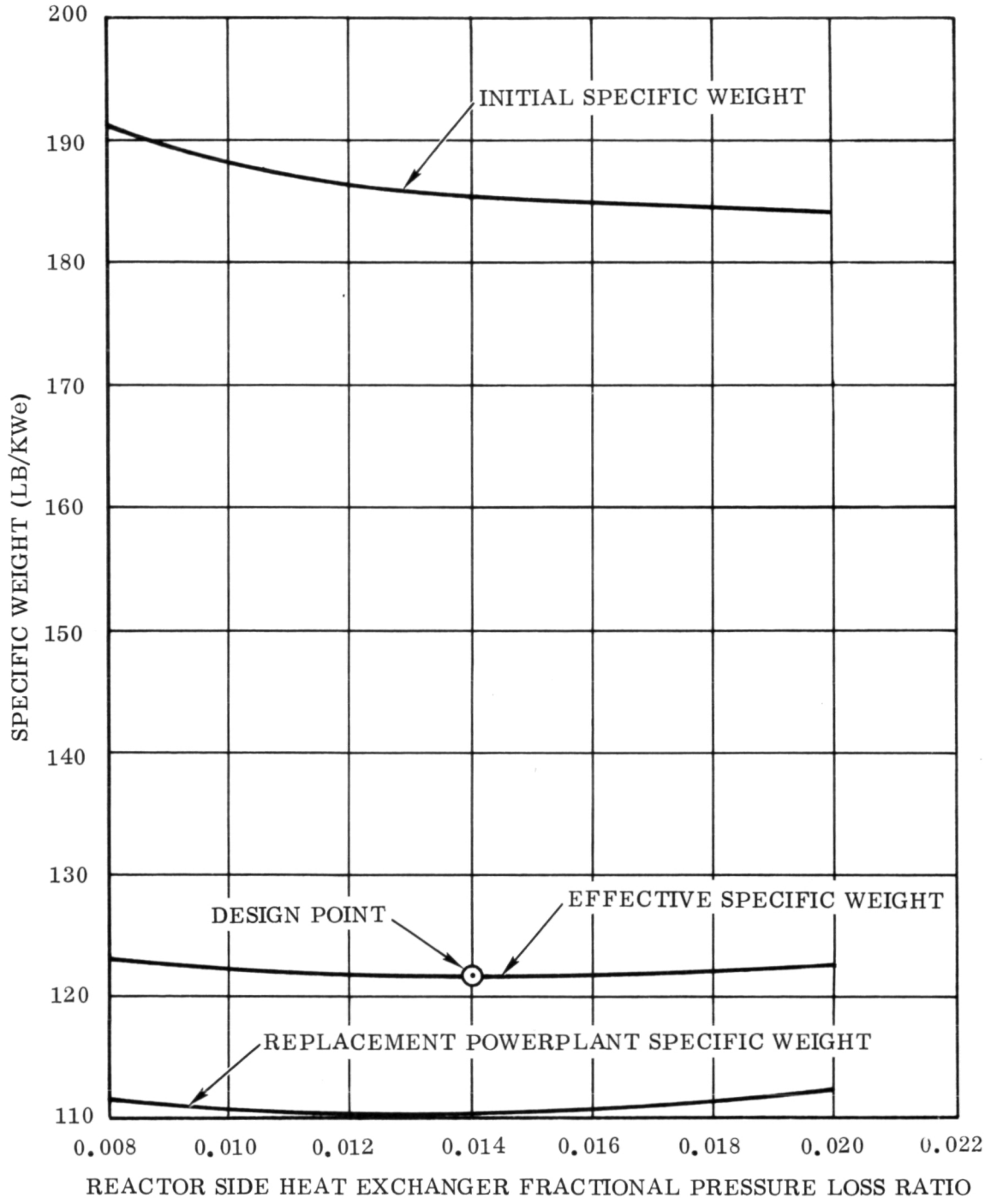

Fig. 4-10 Variation of Specific Weight with Reactor Side Heat Exchanger Pressure Loss Ratio

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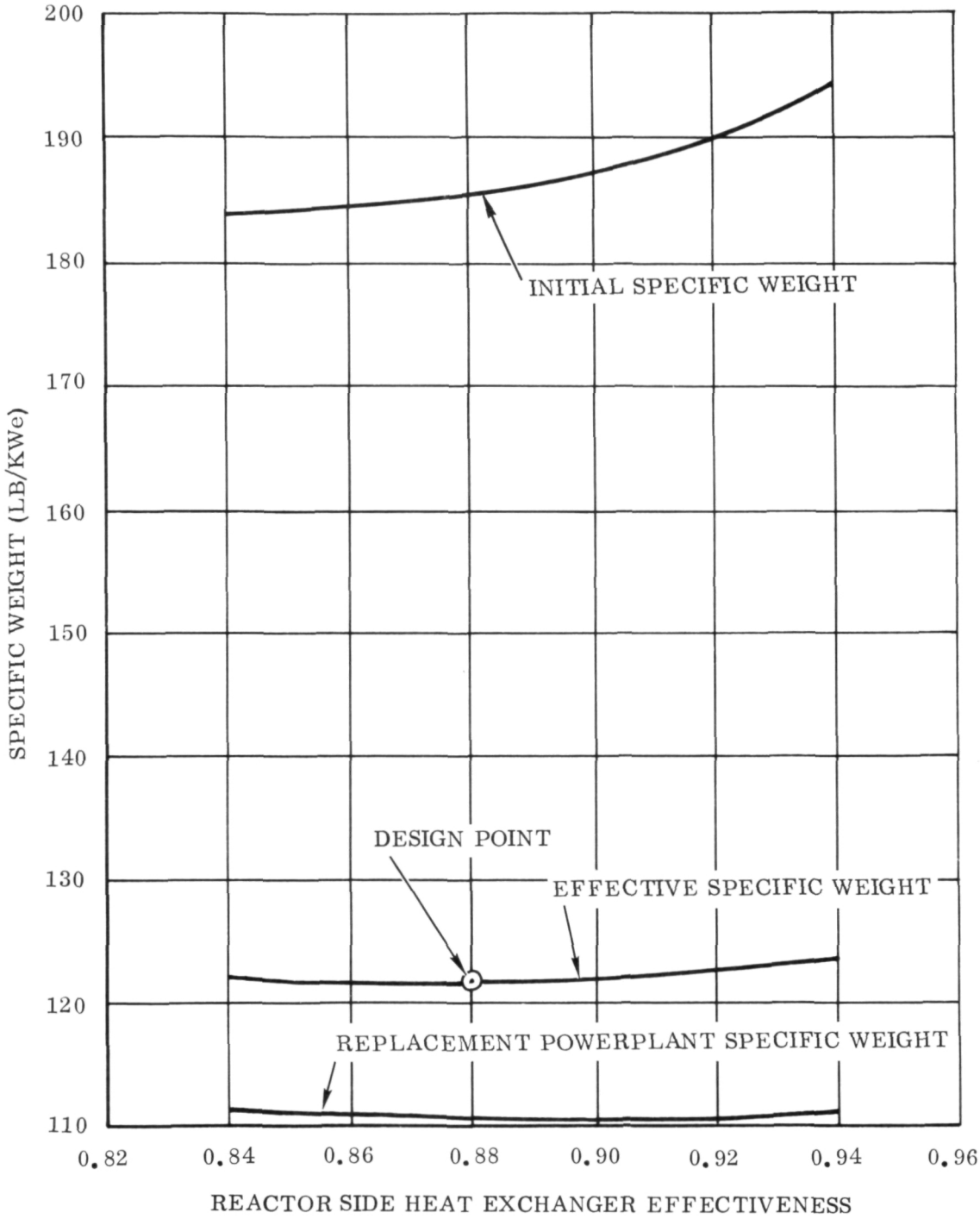

Fig. 4-11 Variation of Specific Weight with Reactor Side Heat Exchanger Effectiveness

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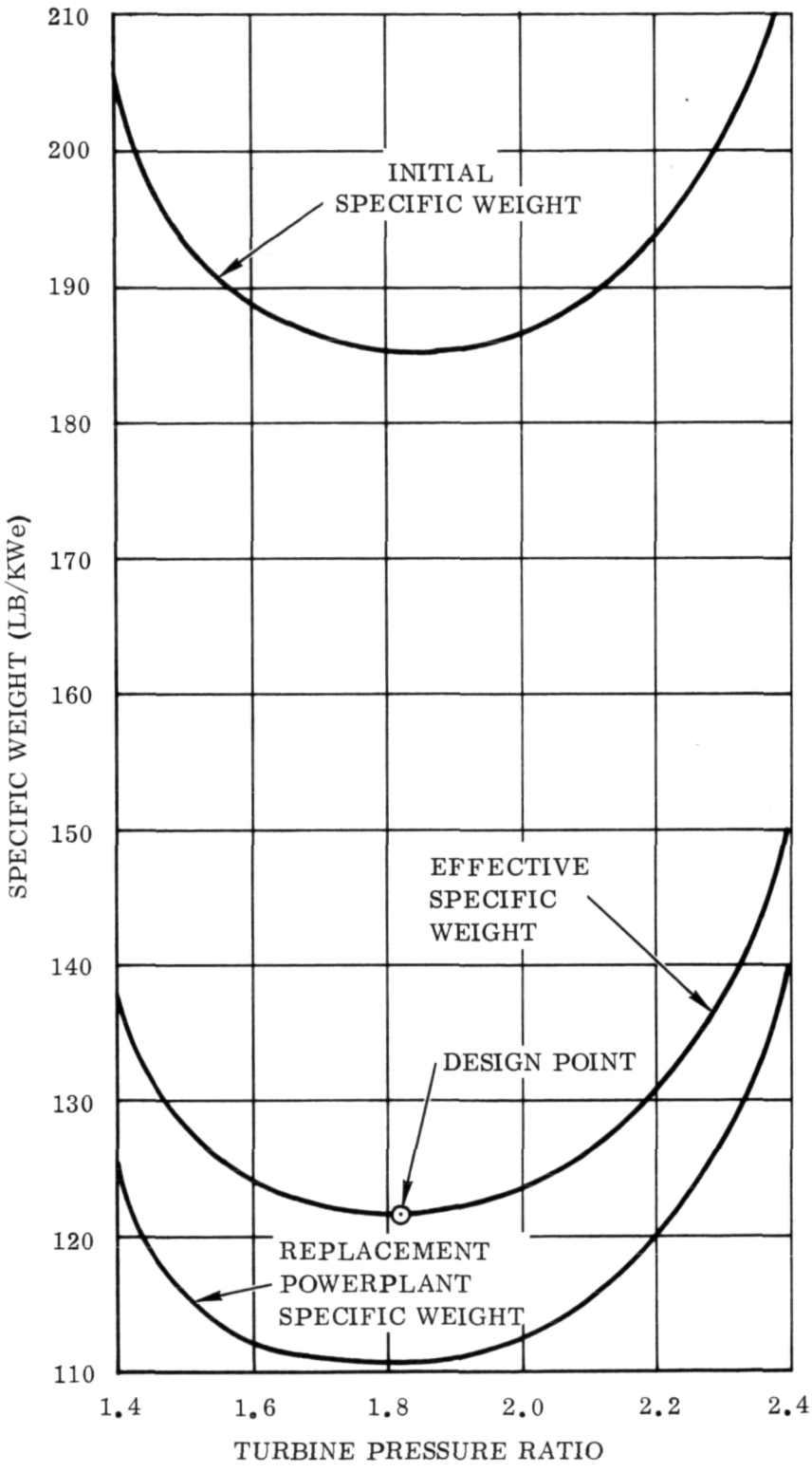

Fig. 4-12 Variation of Specific Weight with Turbine Pressure Ratio

be easy to adapt the powerplant to a set of turbomachinery anywhere within a reasonable range of pressure ratios. Thus an early start can be made on the development of the turbomachinery with the knowledge that later system refinements should not impose large penalties on the initial decision.

The sensitivity to compressor inlet temperature is shown in Figure 4-13. A reasonably rounded optimum exists showing that the system is hardly sensitive to a 25°F error in radiator discharge temperature. The sensitivities to the recuperator fractional pressure drop and effectiveness are shown in Figures 4-14 and 4-15. Since two recuperators are provided a noticeable sensitivity results. The optima are sufficiently broad so that off design component performance should not greatly impair the system output.

The sensitivities to radiator loop heat exchanger fractional pressure drop and effectiveness are shown in Figures 4-16 and 4-17. The system is relatively insensitive to the pressure drop in the heat exchanger. The attractiveness of the separate radiator loop lies in the ability to build a substantially lower pressure drop heat exchanger than gas radiator. The sensitivity to radiator loop heat exchanger effectiveness shows the effects of increased heat exchanger weight and of a uniform lowering of the radiator temperature. Since the temperature change of the NaK in the radiator loop is equal to that of the power conversion system gas in the heat exchanger, small changes in effectiveness affect the temperature levels in the entire radiator.

The influence of system ducting diameter on system weight is shown in Figure 4-18. The large pressure losses associated with small duct sizes can greatly penalize the system. Since two sets of power conversion equipment are provided the ducting weight can become appreciable. The sensitivity to primary loop fluid temperature rise is shown in Figure 4-19. The flat optimum results from the small amount of pump work used by the primary loop and small changes in temperature involved. It appears that large primary loop circulation rates are desireable and that variations in this rate near the optimum can be tolerated.

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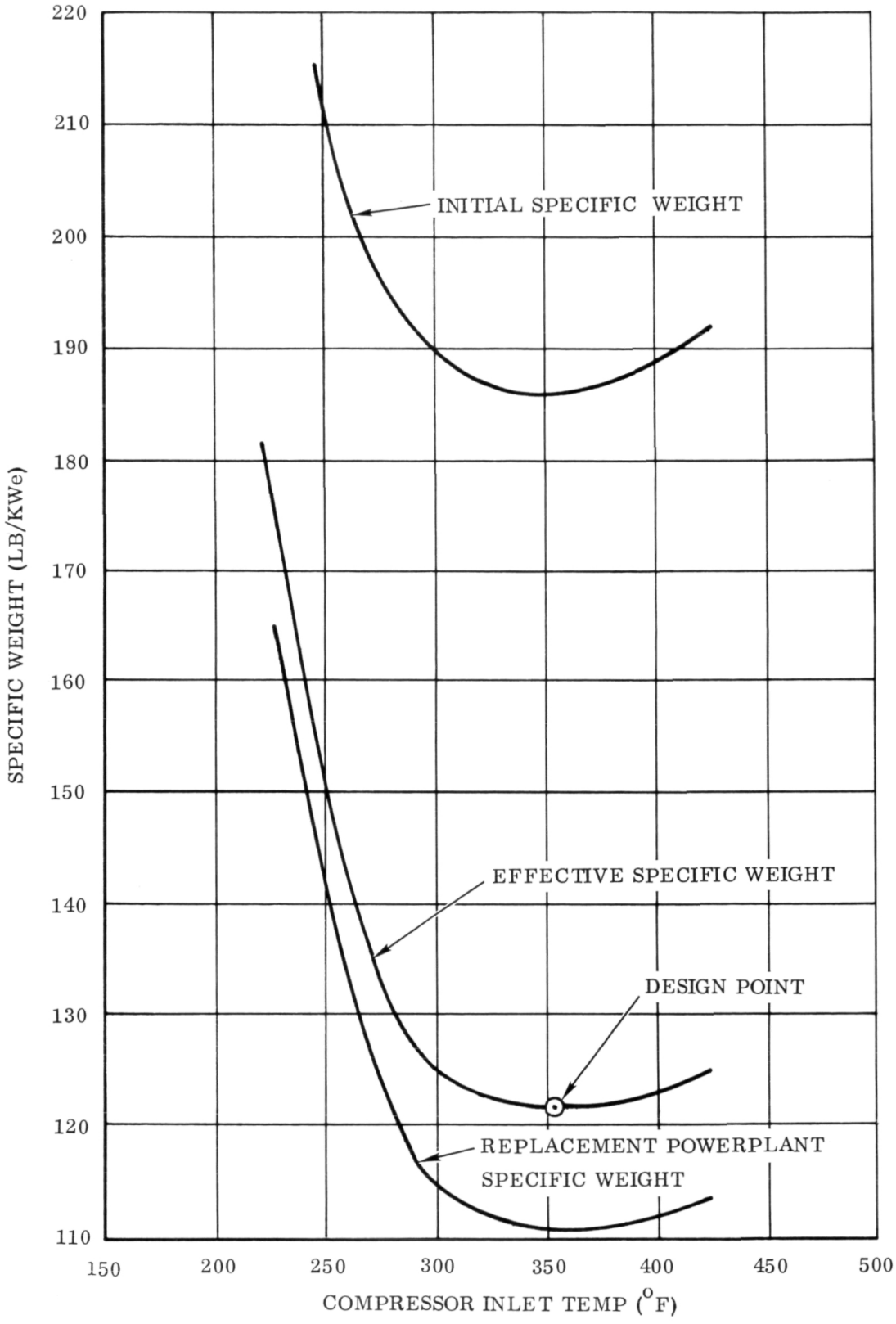

Fig. 4-13 Variation of Specific Weight with Compressor Inlet Temperature

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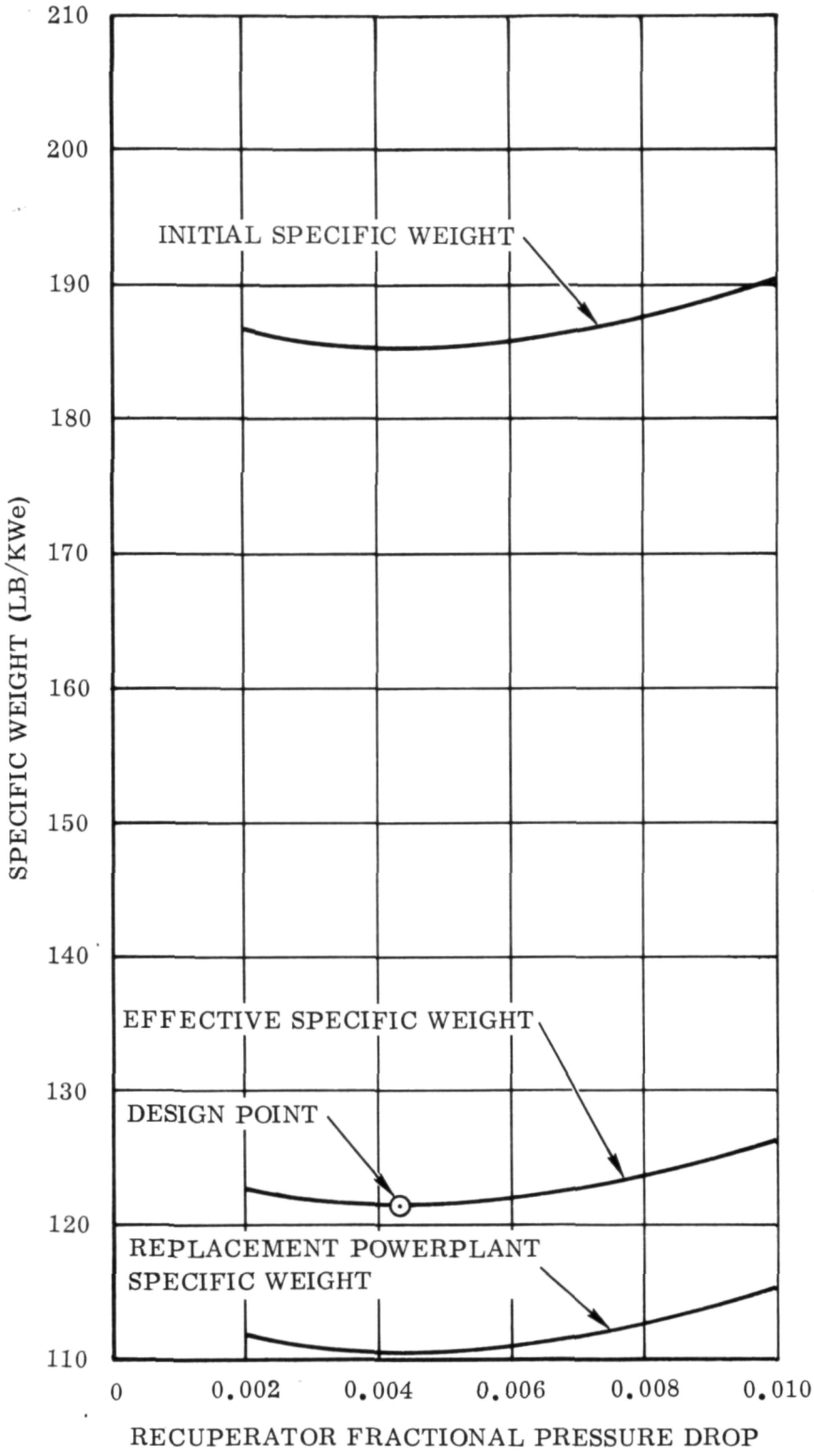

Fig. 4-14 Variation of Specific Weight with Recuperator Pressure Loss Ratio (Each Side)

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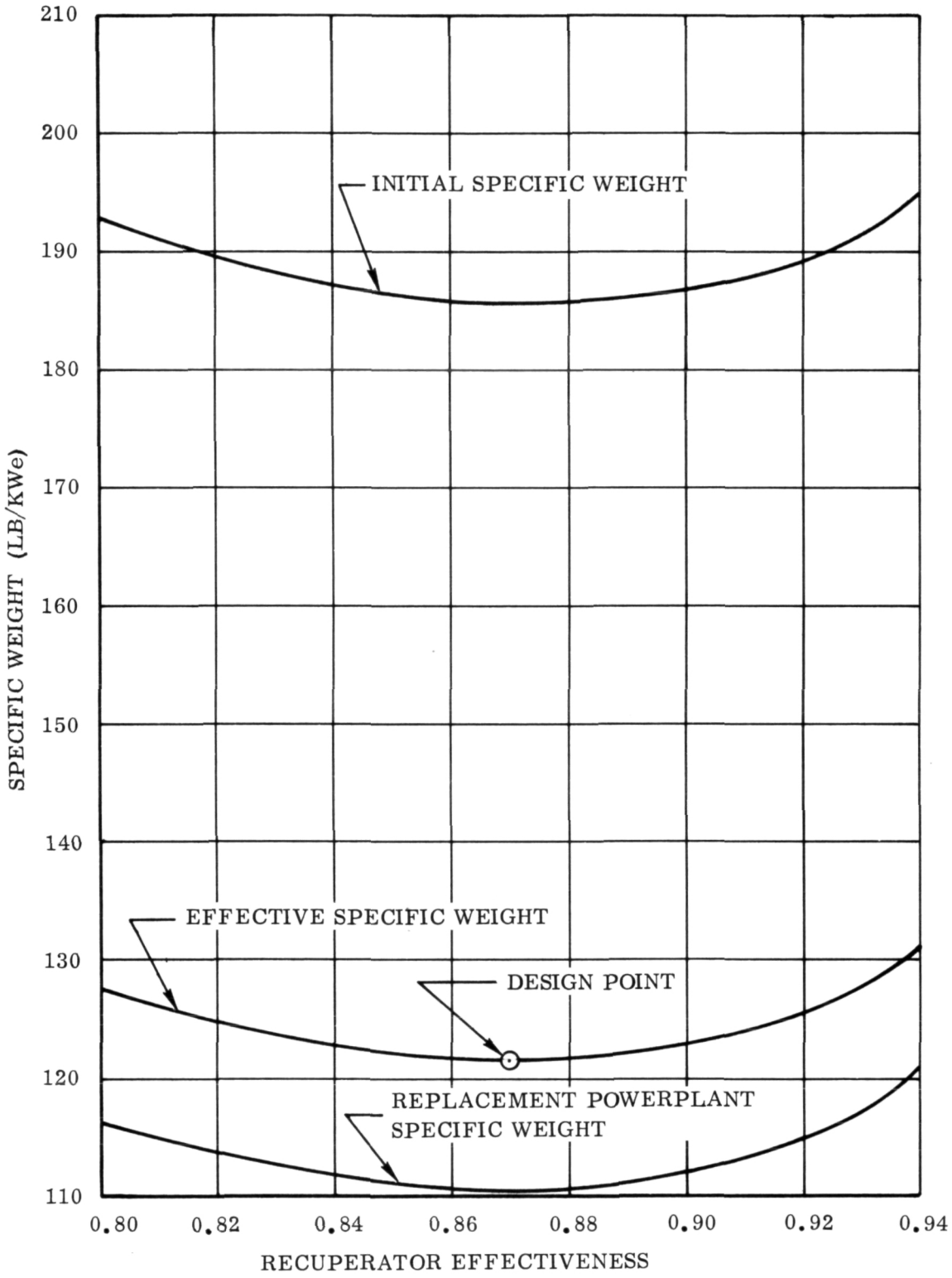

Fig. 4-15 Variation of Specific Weight with Recuperator Effectiveness

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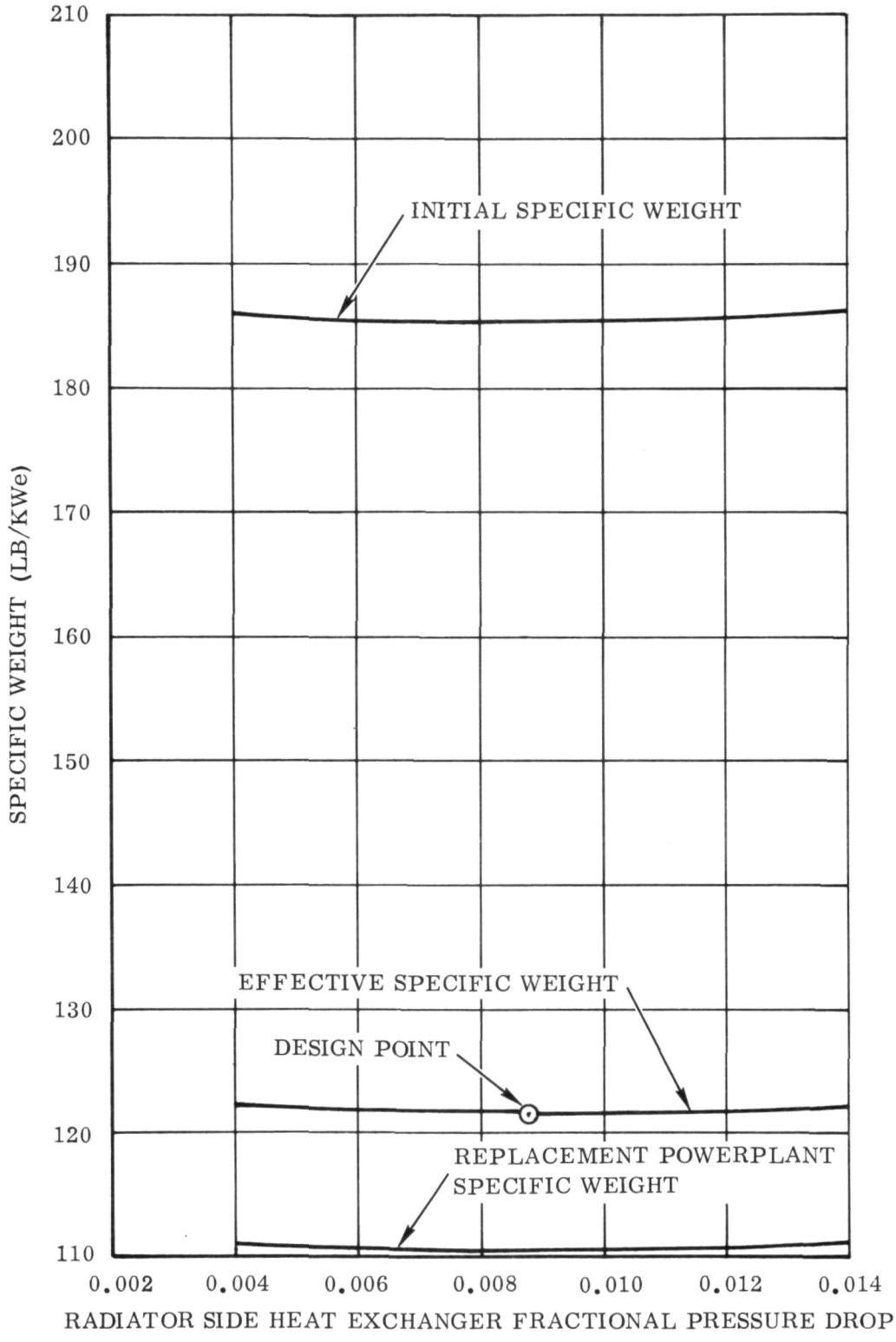

Figure 4-16 Variation of Specific Weight with Radiator Side Heat Exchanger Pressure Loss Ratio

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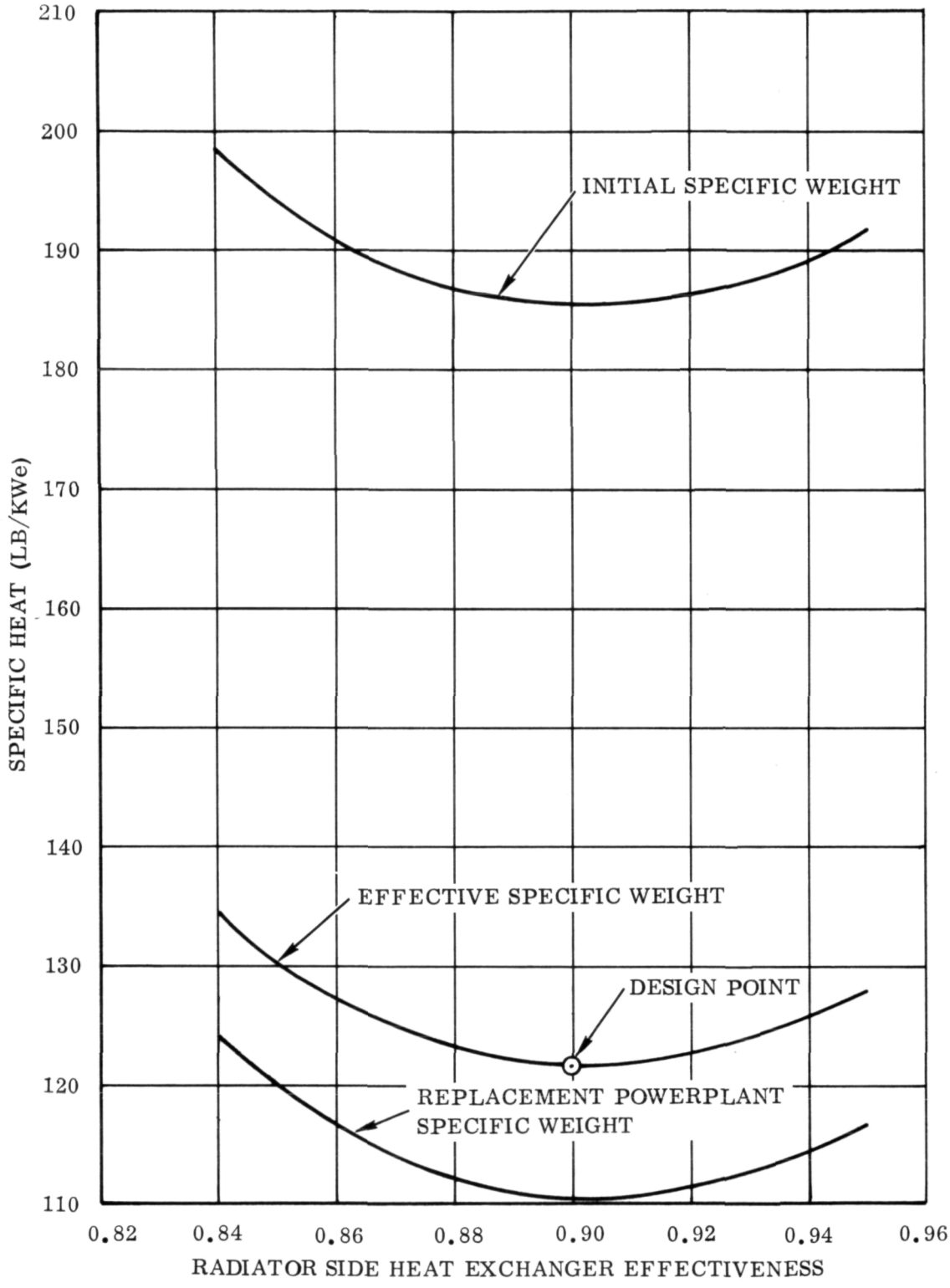

Fig. 4-17 Variation of Specific Weight with Radiator Side Heat Exchanger Effectiveness

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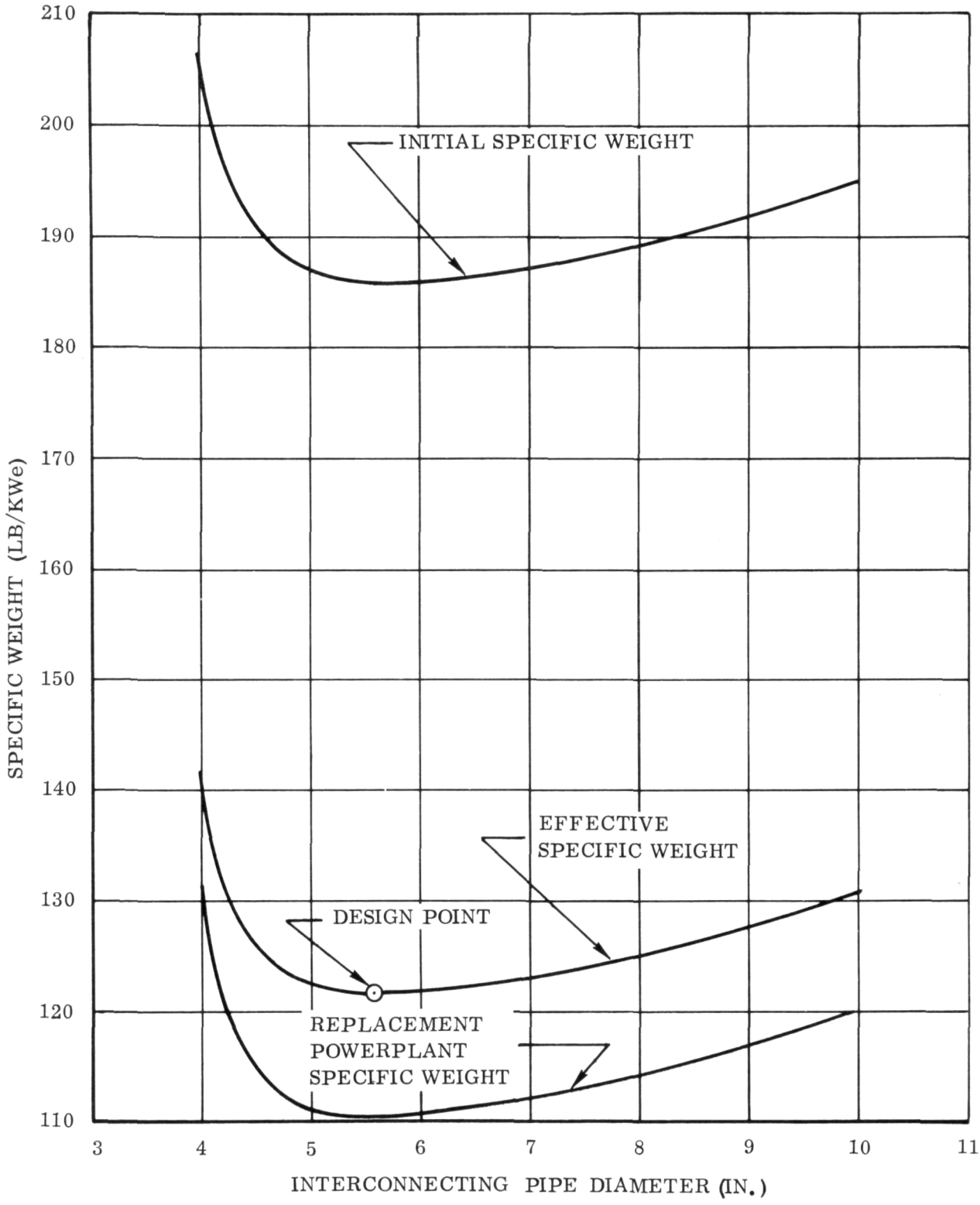

Fig. 4-18 Variation of Specific Weight with Interconnecting Pipe Diameter

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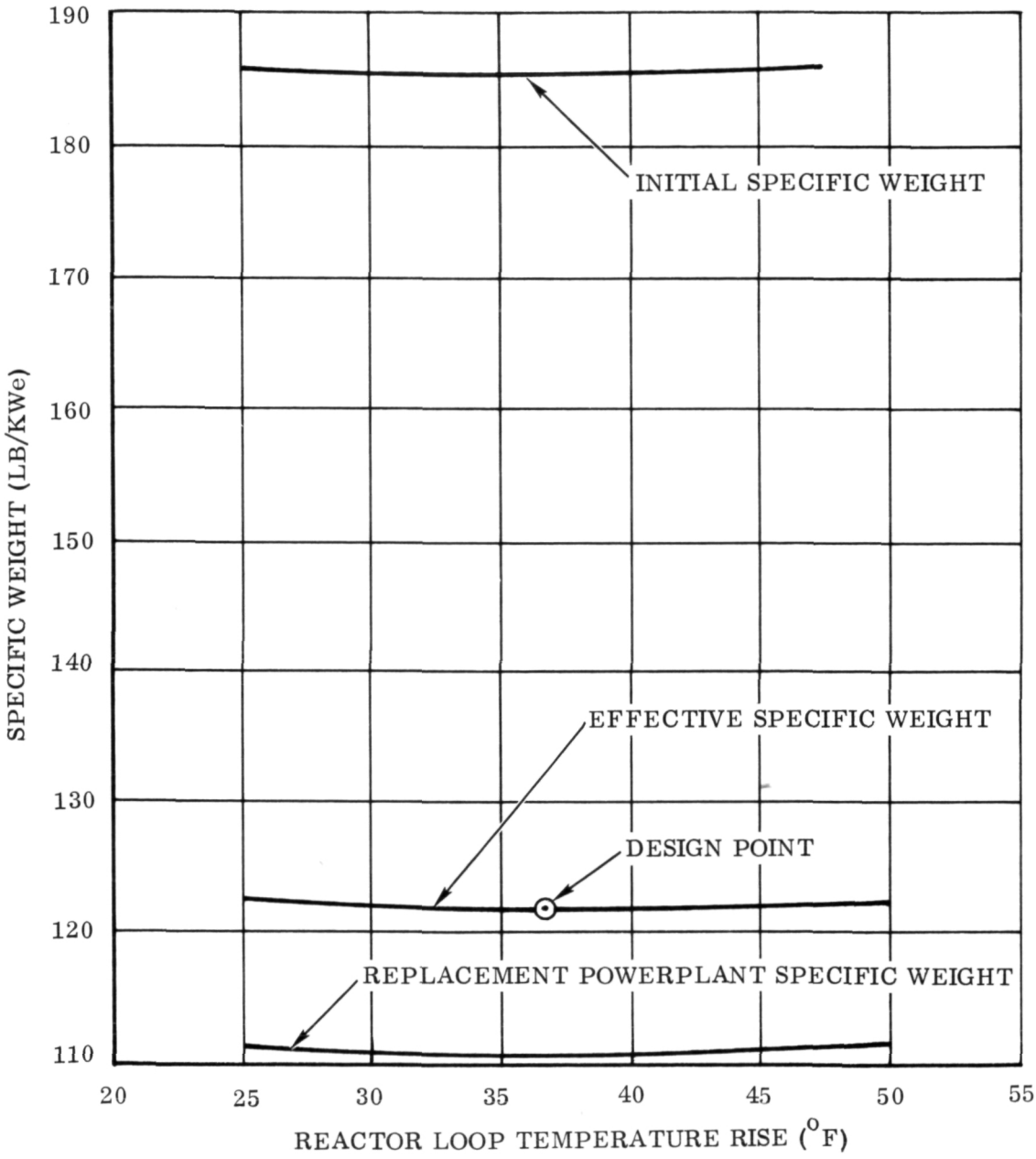

Fig. 4-19 Variation of Specific Weight with Reactor Loop Temperature Rise

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The sensitivities to parasitic fractional pressure drop is shown in Figure 4-20. The importance of this figure is that parasitic pressure loss can be tolerated at little cost in system weight or power. The slope of the curves indicates a sensitivity of about 3% in system weight per 1% additional pressure drop. This increase in system weight would be nearly equal to the loss in power at the same system weight. Thus tolerable power losses are incurred for modest parasitic pressure losses.

The influence of sink temperature on system specific weight is shown in Figure 4-21. At very low sink temperatures the system exhibits little change with sink temperature. This is due to the negligible thermal radiation from sources at these temperatures compared with the radiator heat rejection rates. At higher sink temperatures the incoming thermal radiation has an influence on radiator performance.

Since the radiator outlet temperature is reasonably close to the sink temperature, changes in sink temperature require corresponding changes in the radiator. Increases in radiator temperature result in lower system efficiency and higher reactor power. The changes in reactor power exert large influences on shield weight since additional shielding can only be applied at the periphery, where the diameter is greatest. The influence of sink temperature variations from - 50^{o}F to + 50^{o}F on system specific weight is sufficient to warrant the specification of the space station orbit to be clearly defined before designs are investigated more thoroughly.

4.6 MAINTENANCE, RELIABILITY, AND REDUNDANCY

The powerplant for use on manned missions must possess a high level of confidence in its operation. Low weight or operational advantages are of no importance if the necessary reliability cannot be achieved. Gains in system reliability can be achieved through use of redundant components, as well as through inspection and maintenance procedures. Potential reliability improvements are listed in Table 4-7, and are discussed below.

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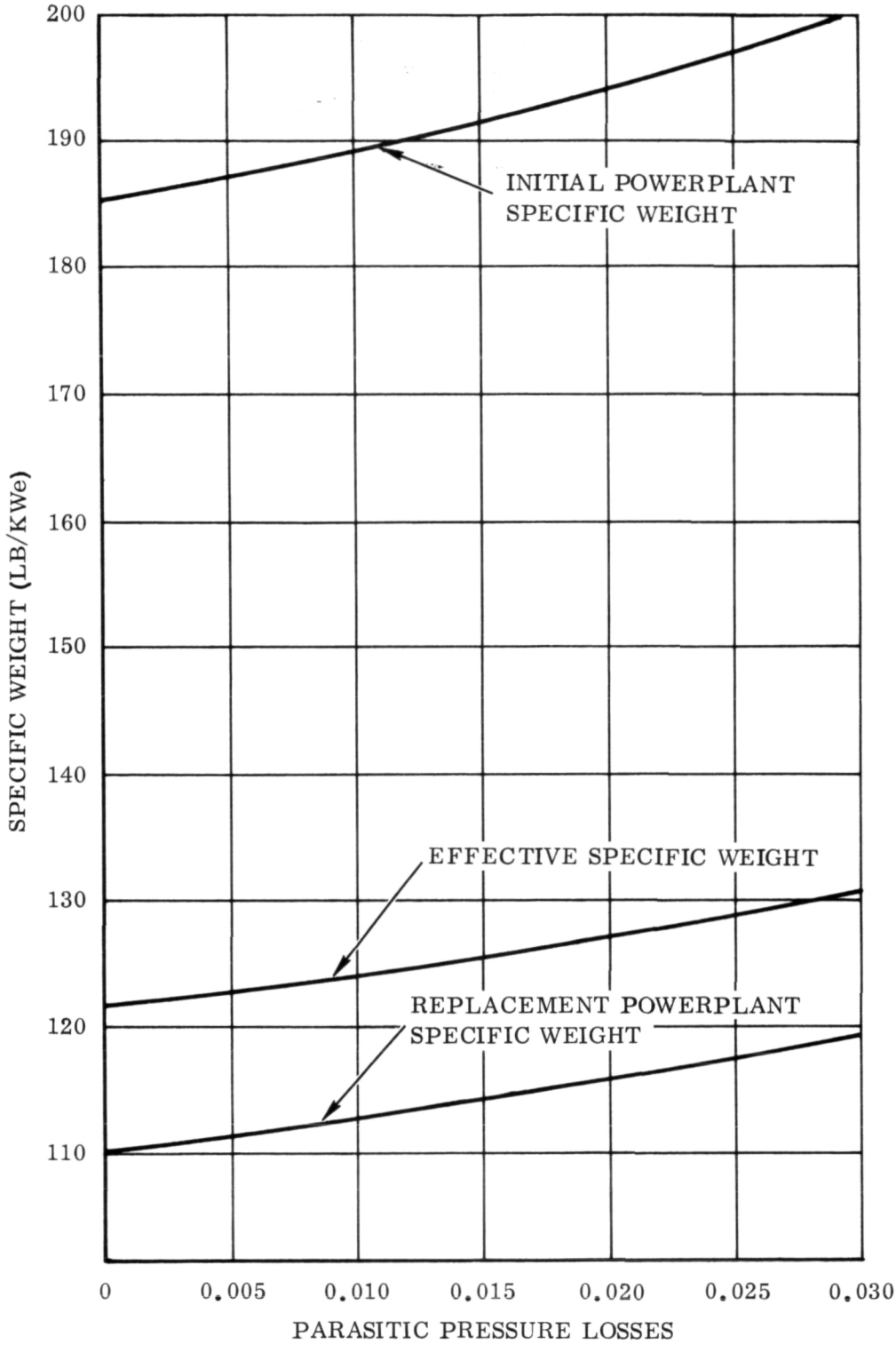

Fig. 4-20 Variation of Specific Weight with Parasitic Pressure Losses

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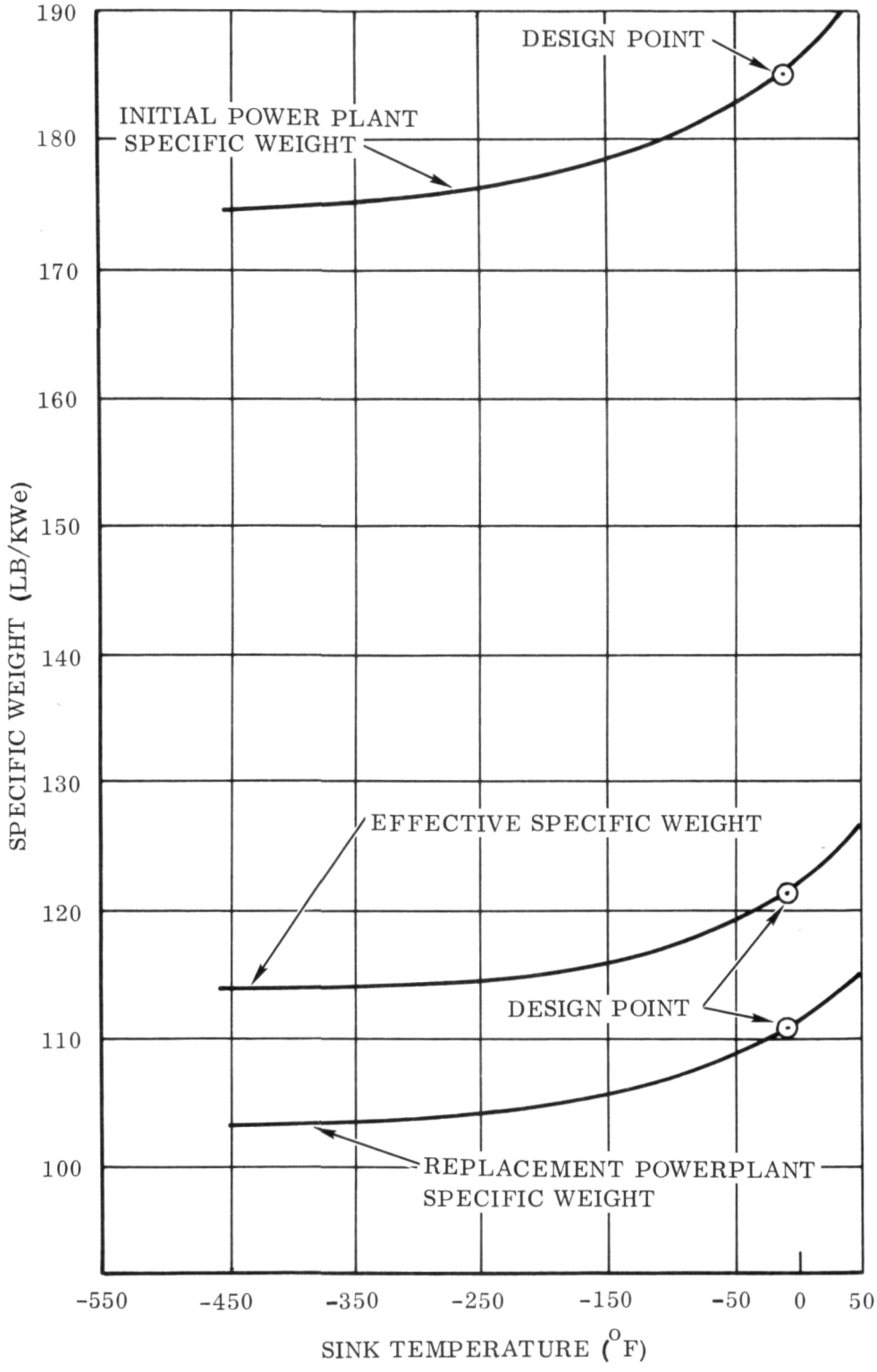

Fig. 4-21 Variation of Specific Weight with Sink Temperature

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Table 4-7. Potential Reliability Improvements

- Redundant Components within Loops
- Redundant Power Conversion Loops
- Instrumentation, Inspection, and Maintenance
- Component Replacement
- Powerplant Replacement

Figures 4-22 and 4-23 illustrate the alternative uses of redundant elements.

4.6.1 REDUNDANT COMPONENTS WITHIN LOOPS

The principal components of a three-loop Brayton cycle power conversion system include:

- Reactor
- Primary loop NaK Pump/Motor/Assembly (PMA)
- Primary loop heat exchanger
- Turbocompressor
- Turboalternator
- Radiator loop PMA
- Radiator loop heat exchanger
- Radiators
- Secondary radiator loop PMA

Only systems with a single reactor have been considered since the additional shield weight for an additional reactor would be prohibitive. The reactor has a great deal of redundancy built into it since it consists of multiple fuel elements and reflectors. The primary loop is isolated from the space station so that fuel element leakage will not result in irradiation of the space station.

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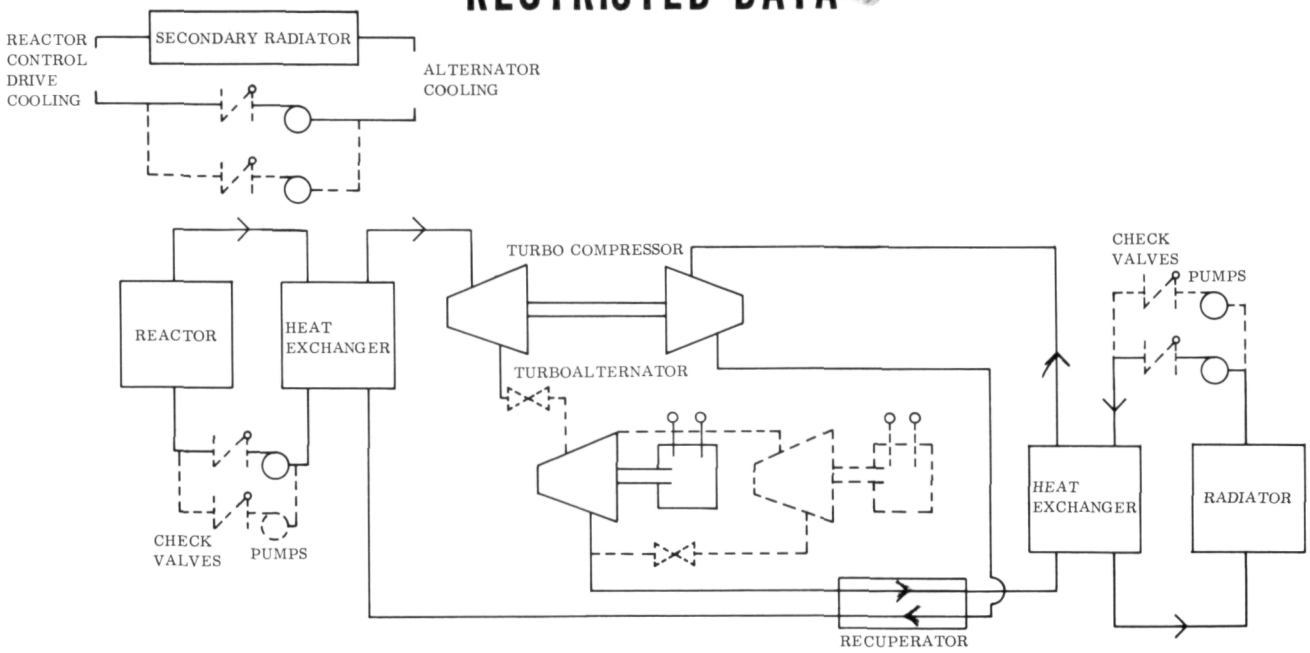

Figure 4-22. Redundant Components Within Loops

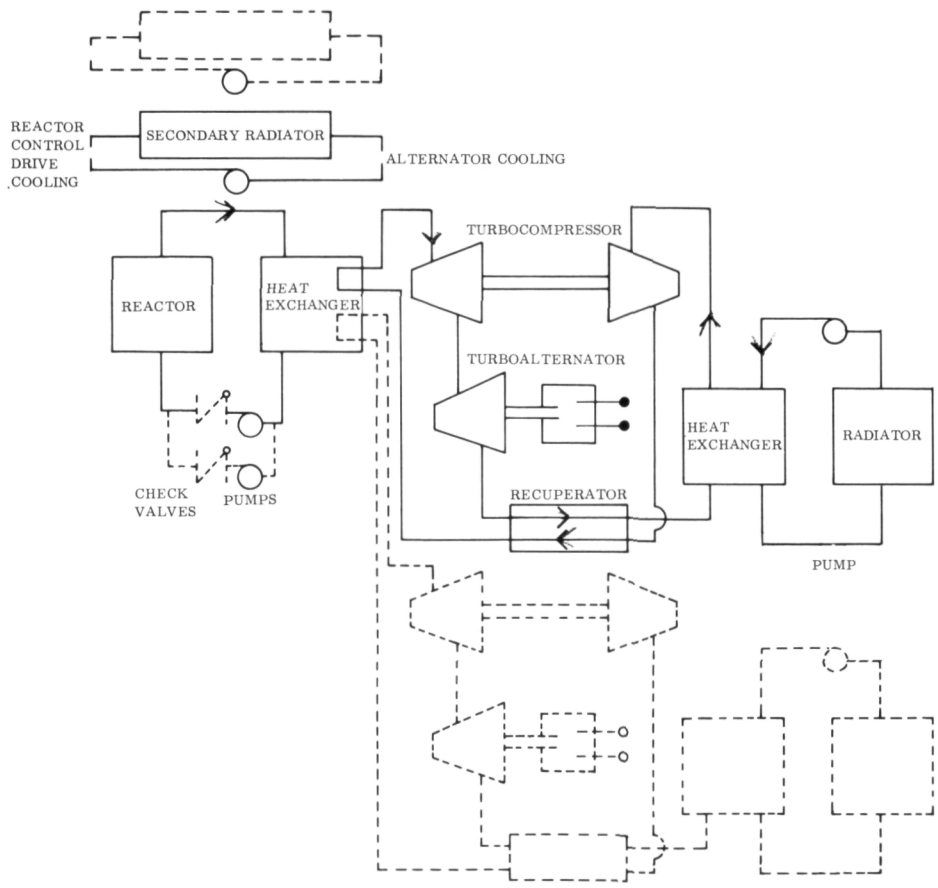

Figure 4-23. Redundant Loops

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Reactor failure can occur due to primary loop failure (pump failure or loop leaks) or failure of the control system. In order to reduce the control system failure, a 2 out of 3, or 3 out of 4, voting logic on sensors would be used. Since the loss of the primary loop coolant would result in system failure, the use of redundant pumps and check valves permits continuous operation in the event of failure of a PMA. Comparisons of standby and parallel working redundancy is shown in Figures 4-24 and 4-25. Standby redundancy requires a sensing element to detect failure and activate the standby component. The ratio of the failure rate of the sensing and switching system is assumed to be related to the component failure rate by

$$n = \frac{\text{Failure rate of sensing and switching system}}{\text{Failure rate of component}}$$

No switching is required for working redundancy.

The loss of the primary loop heat exchanger would result in eventual loss of the primary loop coolant and plant shutdown. Valving of the heat exchanger is possible by the reliability of high temperature NaK shut-off valves for use after long periods of exposure to high temperatures, and nuclear fluxes may not be high enough. Pinchoff techniques may be possible for shutting off lines.

Turboalternator and turbocompressor redundancy provisions can be made much easier in a standby basis than on a working basis since control of two turbomachines operating in parallel would be complex. With standby machines there are two failure modes possible:

1. Both machines fail, one after the other
2. The sensing and switching system fails before the first machine fails and redundancy is lost

If check valves are used the reliability is the same as that of the primary PMA. If shutoff valves are required then the valve reliability must be included in the analysis.

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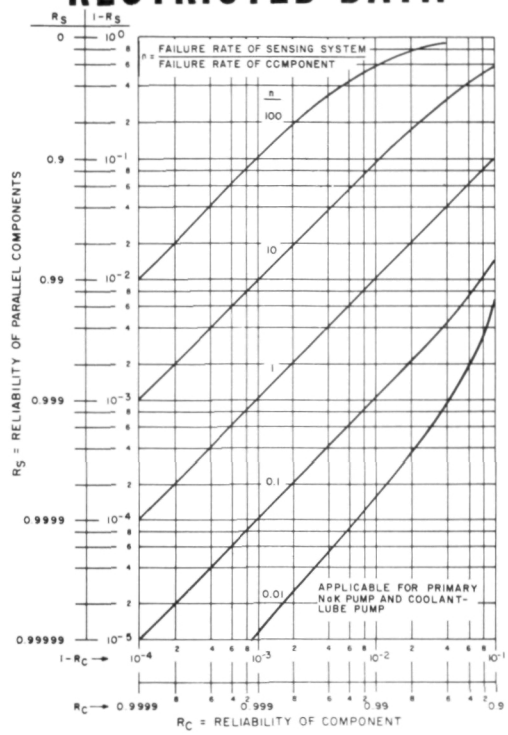

Figure ~~4-24~~. Reliability of Parallel Components with Second Component in Standby

Figure 4-24. Reliability of Parallel Components with Second Component in Standby

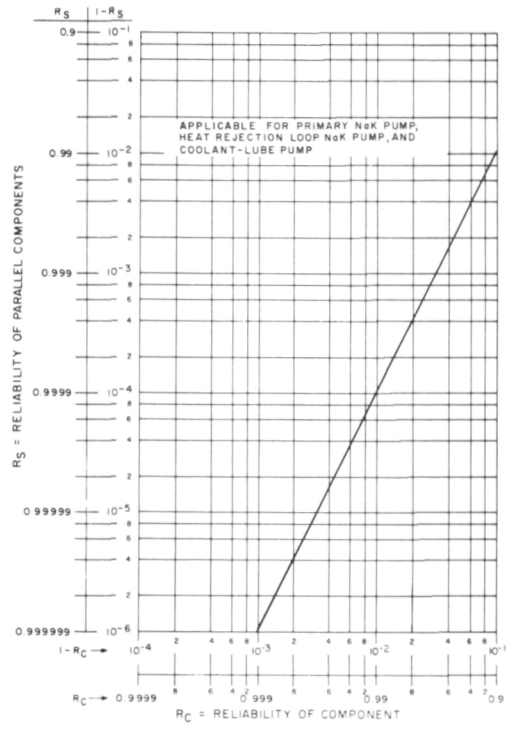

Figure ~~4-25~~. Reliability of Parallel Components with Both Components Operating

Figure 4-25. Reliability of Parallel Components with Both Components Operating

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Reliability considerations on the radiator loop pumps and heat exchanger are the same as those for the reactor loop components, since only a single radiator can be accommodated by the launch vehicle. Radiator reliability, like that of the reactor must be exceedingly high since redundancy cannot be directly provided.

4.6.2 REDUNDANT LOOPS

It is impractical to provide a redundant primary NaK loop, as is discussed in 4.6.1 above, because of the shielding penalties on the second reactor.

Theoretically any number of power conversion loops could be connected to the primary loop. The following practical considerations must be considered however.

The primary heat exchanger must be shielded. Since the gas side of the heat exchanger occupies an appreciable volume the addition of loops required substantial shield enlargement.

Increase in the number of heat exchangers does not reduce the probability of heat exchanger failure since the active heat exchanger surface would still operate at design conditions. Increase in the number of joints, welds, and surface area increases the likelihood of random failure due to materials or assembly imperfections. A single heat exchange failure can result in reactor shutdown.

The radiator area must be shared by the power conversion loops. This requires independent parallel tubes, headers, etc. As the number of loops is increased the available space for the tubes and feed, and the accessibility of the tubes and feeds decrease. The difficulty of assembling and inspecting a multichannel distribution system increases with the number of loops. It appears that two parallel power conversion loops could be employed to obtain the major reliability improvement and that additional loops would result in unnecessary system complexity.

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Operation of multiple power conversion loops with standby redundancy results in the same reliability gains as would be found for a single component standby redundancy, with a 100% reliable sensor and switching controller in a component redundancy method. Since multiple components in the power conversion loop could fail, the overall reliability of the component redundancy technique is less than that of the redundant loop technique. The redundant loop technique needs only one sensor; alternator power and space station crew provide an excellent backup for such a sensor, to initiate shutdown of one loop and startup of the other. For these reasons the parallel loop redundancy design with two power conversion loops was selected for the manned space station powerplant.

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5. SCIENTIFIC PROBE POWERPLANT CONCEPTUAL DESIGN

The unmanned mission selected for the powerplant design is that of a scientific probe which uses the power for terminal propulsion, instrumentation, and communication. Startup of the powerplant is to be initiated 10,000 hours after launch. The vehicle for such a mission only requires shadow shielding and therefore the powerplant weight does not show the same sensitivity of shield weight to reactor size. The minimum weight system for this mission is one with a cermet fueled reactor which is capable of delivering gas at 2200°F, the highest turbine inlet temperature under consideration. The parametric results show that a small weight savings can be obtained by using a separate liquid metal radiator loop; however the requirement of 10,000 hours wait in space prior to startup results in the expectation of NaK freezeup (especially on outbound missions). Systems to maintain the NaK molten, or melt it prior to startup, easily use up the weight advantage of the additional loop.

One set of turbomachinery is provided for the one-loop system. Additional sets of turbomachinery could be used to provide a redundant power conversion system; however, the large valves required could present pressure drop and reliability problems. The sensing and switching device would have to have a higher reliability than that of the turbomachinery. The level of confidence and reliability of the turbomachinery will have to be extremely high to begin with before any mission requiring the powerplant, requiring the expensive development program of a scientific probe, and using Saturn V launch vehicles is committed. The possibility of having two sets of turbomachinery operate in parallel, with the system at half the pressure level required for a single machine was examined.

The increases in component weight, at the reference design condition, before reoptimization, of 30% for the reactor and shield, 70% for the radiator, and 80% for the recuperator, accompanying this decrease in system pressure appeared sufficient to abandon further examination of parallel working redundancy at reduced system pressure level for power sizes below 200 KW. Reoptima of this nature typically result in a savings of 30% of the added weight. This increase in system weight appears to be great enough to reduce the scientific payload to the point where the value of the mission is questionable.

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5.1 200KWE UNMANNED CONFIGURATION DESCRIPTION

The conceptual design of a 200 KWe unmanned system is illustrated by Figure 5-1. In the launch configuration, the spacecraft has an overall length of 53.5 ft. and a base diameter of 260 in. to mate with the S-IVB stage of the Saturn V booster. To minimize nuclear radiation shielding weight and provide an efficient structure, a cone half angle of 10° is used. The powerplant radiators form the vehicle shell and serve as the support structure for the reactor, shield and power conversion equipment.

The lower three radiator bays are used for rejecting cycle waste heat. Each bay provides 559 ft^2 of area and rejects approximately 242KW of thermal energy. Hot gas is carried to the radiators by means of large diameter feed lines running along the inner surface of the radiator. Differential expansion between the steel feed lines and the aluminum radiator matrix is accomodated by the bellows joints shown in Detail A. Gas flow to the individual radiator tubes is by means of circumferential headers, each spanning 180° of the vehicle. Pigtail connections are used between the headers and tubes to facilitate assembly and reduce thermal stress in the members. Meteoroid protection for the feeds, headers and pigtails is provided by the thin-walled bumpers shown in Detail B. These bumpers, in conjunction with the radiator fins and header cover plates, provide a degree of protection commensurate with the mission requirements.

Secondary cooling loads such as alternator and bearing losses are rejected from the 300ft^2 upper radiator bay. This radiator, sized to reject 50KW, uses an organic coolant. Inlet temperature is taken as 400° F and a coolant temperature drop of 29° F is used. Due to the reduced cross-sectional area of the radiator at the upper portions of the vehicle, a significant amount of structure has been added to the secondary radiator to sustain the launch loads.

The power conversion equipment is located within the secondary radiator. Support is provided by means of an open framework supported by struts from the radiator header rings. To prevent radiation scattering, gas lines to the reactor are each spiraled 180° and recessed in the radiation shield. This proximity to the shield may induce local heating problems,

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however, use of multi-layer foil insulation and active cooling from the secondary radiator loop can provide the necessary thermal control. Reactor control drum drive motors are located behind the radiation shield. Stepped shafts through the shield provide actuation for the passively cooled reflectors and prevent radiation streaming.

Payload systems are located in a deployable module nested within the lower bay of the primary radiator during the initial stages of flight. In this position, the payload module is given lateral and axial support by webs attached to the primary radiator. Axial loads from the primary radiator are transmitted to the booster through an adapter ring. Separation from the launch vehicle is accomplished by a shaped charge severing the adapter ring. Deployment of the payload to its operational position is by means of mechanical linkage. In the flight configuration, the payload module is approximately 20 feet from the powerplant. Control of thermal energy interchange between the powerplant radiators and the payload module can be accomplished with low emissivity coatings on the inner surface of the radiators and multi-layer foil insulation on the payload module and radiator interior surface. Cooling requirements of the payload system can be accommodated by radiators on the conical surface of the payload module; an area greater than 300 ft^2 is available for this purpose.

As illustrated, the payload consi sts of a lander, two 10-ft parabolic dish antennas, computers, data processing equipment and scientific instrumentation. Three banks of electric engines and propellant supply tanks are also located at the base of the payload module. Propellant tanks and instrumentation are located so as to counteract the moments developed by the lander, thereby minimizing eccentric loads on the booster. Antenna deployment is accomplished by rotations of the multi-hinged boom, which when fully extended provides a 7-1/2 ft. clearance from the vehicle. Pivot points at the end of the boom provide antenna directional control. Lander deployment is accomplished by pivoting the support assembly clear of the payload module before release.

The weight summary of the 200 KWe powerplant is given in Table 5-1, and the mission vehicle weight summaries are given in Table 5-2.

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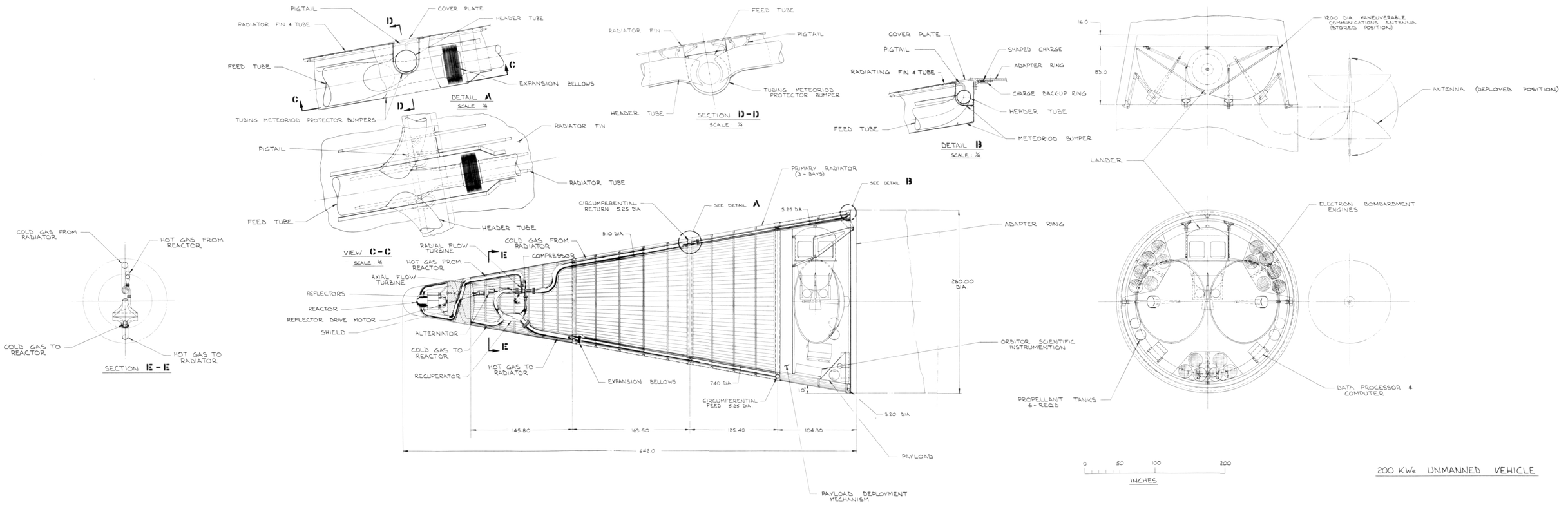

Figure 5-1. Conceptual Design of Brayton Cycle Powerplant for Unmanned Scientific Probe

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Table 5-1. Design Parameters for 200 KWe Unmanned System

		Units	With Power Flattened Reactor	With Uniform Fuel Loaded Reactor
Optimized Parameters	Reactor Pressure Loss Ratio	%	1.537	1.326
	Turbine Pressure Ratio	------	1.961	1.843
	Compressor Discharge Temp	^{o}F	762	762
	Radiator Pressure Loss Ratio	%	.985	.910
	Recuperator Effectiveness	%	90.6	90.6
	Recuperator Pressure Loss Ratio (Each Side)	%	1.428	1.116
	Interconnecting Pipe Diameter	In.	5.7	6.0
Fixed Input Parameters	Electrical Power Output	KWe	200	200
	Working Fluid	-------	Neon	Neon
	Compressor Efficiency	%	80.0	80.0
	Turbine Efficiency	%	86.91	86.91
	Alternator Efficiency	%	88.0	88.0
	Compressor Discharge Pressure	Psia	295	295
	Reactor Maximum Clad Temp	^{o}F	2,600	2,600
	Reactor Minimum Core Diameter	In.	19.0	11.0
	Reflector Thickness	In.	10.2	10.2
	Recuperator Material	-------	Nickel	Nickel
	Sink Temperature	^{o}F	-10	-10
	Available Primary Radiator Area	Ft^2	1,677	1,677
	Radiator Mean Time to Failure	Hrs	200,000	200,000
	Shield Materials	------	LiH/W	LiH/W
	Mission Time	Hrs	10,000	10,000
	Turbine Inlet Temp	^{o}F	2,200	2,200
Dependent Parameters	Turbine Discharge Temp	^{o}F	1,669	1,698
	Radiator Inlet Temp	^{o}F	843	850
	Compressor Inlet Temp	^{o}F	407	424
	Reactor Inlet Temp	^{o}F	1,588	1,610
	Compressor Pressure Ratio	-------	2.071	1.949
	Reactor Weight	Lbs	5,220	1,991
	Reactor Core Diameter	In.	20.28	12.89
	Reactor Thermal Power	KWth	915	952
	Overall Reactor Diameter	In.	30.48	23.09
	Radiator Thermal Load	KWth	692	725
	Effective Radiating Temp	^{o}F	994	1,012
	*Primary Radiator Area	Ft^2	1,677	1,677
	Total Primary Radiator Weight	Lbs	4,007	3,865
	Parasitic Structure Weight	Lbs	261	261
	Load Carrying Structure Weight	Lbs	264	224
	Recuperator Weight	Lbs	693	635
	Interconnecting Pipe Weight	Lbs	437	533
	Secondary Radiator Weight	Lbs	525	525
	Shield Weight	Lbs	3,072	1,989
	Mass Flow Rate	Lbs/Hr	21,156	23,662
	Cycle Efficiency	%	24.7	23.8
	Turbomachinery & Alternator Weight	Lbs	850	850
	Total System Weight	Lbs	14,804	10,388
	System Specific Weight	Lbs/KWe	74.0	51.9

*Including Parasitic and Load Carrying Structure.

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Table 5-2. 200 KWe Vehicle Weight Summary

Powerplant		8,400
Reactor	1,990	
Turbomachinery	350	
Alternator	500	
Recuperator	635	
Piping	535	
Primary Radiator Matrix & Feeds	3,380	
Primary Radiator Structure	485	
Secondary Radiator Matrix & Feeds	310	
Secondary Radiator Structure	215	
Shield		1,990
Propulsion System		14,810
Thrustors (Specific impulse 4100 sec)	400	
Propellant & Tankage	14,100	
Power Conditioning & Bus Bars	300	
Payload Systems		3,000
Landing Capsules	2,000	
Antennas	430	
Communications & Instrumentation	480	
Radiators	90	
Spacecraft		4,500
Payload Support Structure	4,000	
Power Conversion Equip. Support Structure	200	
Initial Flight Weight		34,700
Aerodynamic Fairing		300
Launch Weight		33,000

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5.2 SYSTEM WEIGHT VARIATION WITH RADIATOR CONE ANGLE

To determine the optimum cone angle for the reference design 200 KWe vehicle,powerplant weights were determined for values of cone half angle varying from 10° to 25° with the primary radiator area. The variation of primary radiator area with cone angle is shown in Figure 5-2. The curve is based on a payload envelope of 260-inch bus diameter and a maximum overall length of 652 inches. Compensation is made for the area lost to the reactor/shield assembly and the secondary radiator.

Figures 5-3 and 5-4 show the total system weight variation as well as the component weight variations for designs using a uniform fuel loaded reactor with temperature flattening (Figure 5-3) and a uniform coolant passage flattened reactor (Figure 5-4). In both cases, it is seen that system weight is minimized for shallow cone angles, and this weight reduction is due primarily to savings in the shield and radiator.

The shield weight is seen to reduce with cone angle until the very shallow angles are reached, then a slight increase is noted; this is due to an increase in reactor power level at the lower radiator area design points.

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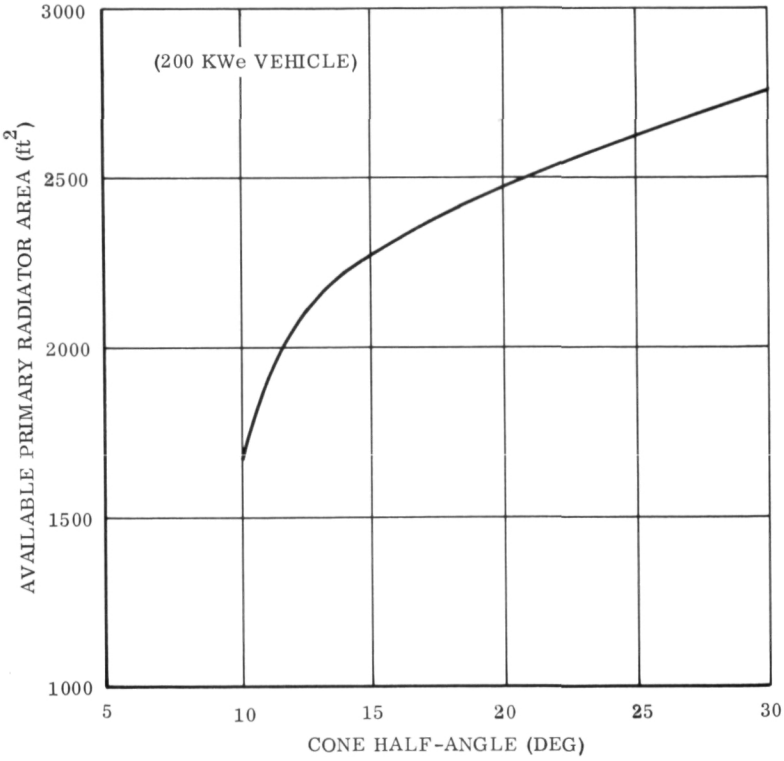

Figure 5-2. Primary Radiator Area Variation with Cone Angle (200 KWe Vehicle)

Figures 5-5 and 5-6 give a more detailed weight breakdown of the radiator subsystem. As the available radiating area is reduced, the optimized cycle conditions shift to increase the effective radiating temperature and higher fin efficiencies are required. This latter effect is accounted for by the area limit model which increases the radiator matrix weight. This increase in matrix density has a compensating effect in that it reduces the amount of additional load carrying structure which must be added. As shown by Figures 5-5 and 5-6, the additional load bearing structure which must be added is reduced from 1300 pounds, at the 25^{o} cone angle, to 400 pounds, at the 10^{o} cone angle.

For the reference design layout, a 10^{o} half cone angle was selected. This value is very near the optimum, and results in an all-conical vehicle thereby simplifying the radiator bay arrangements.

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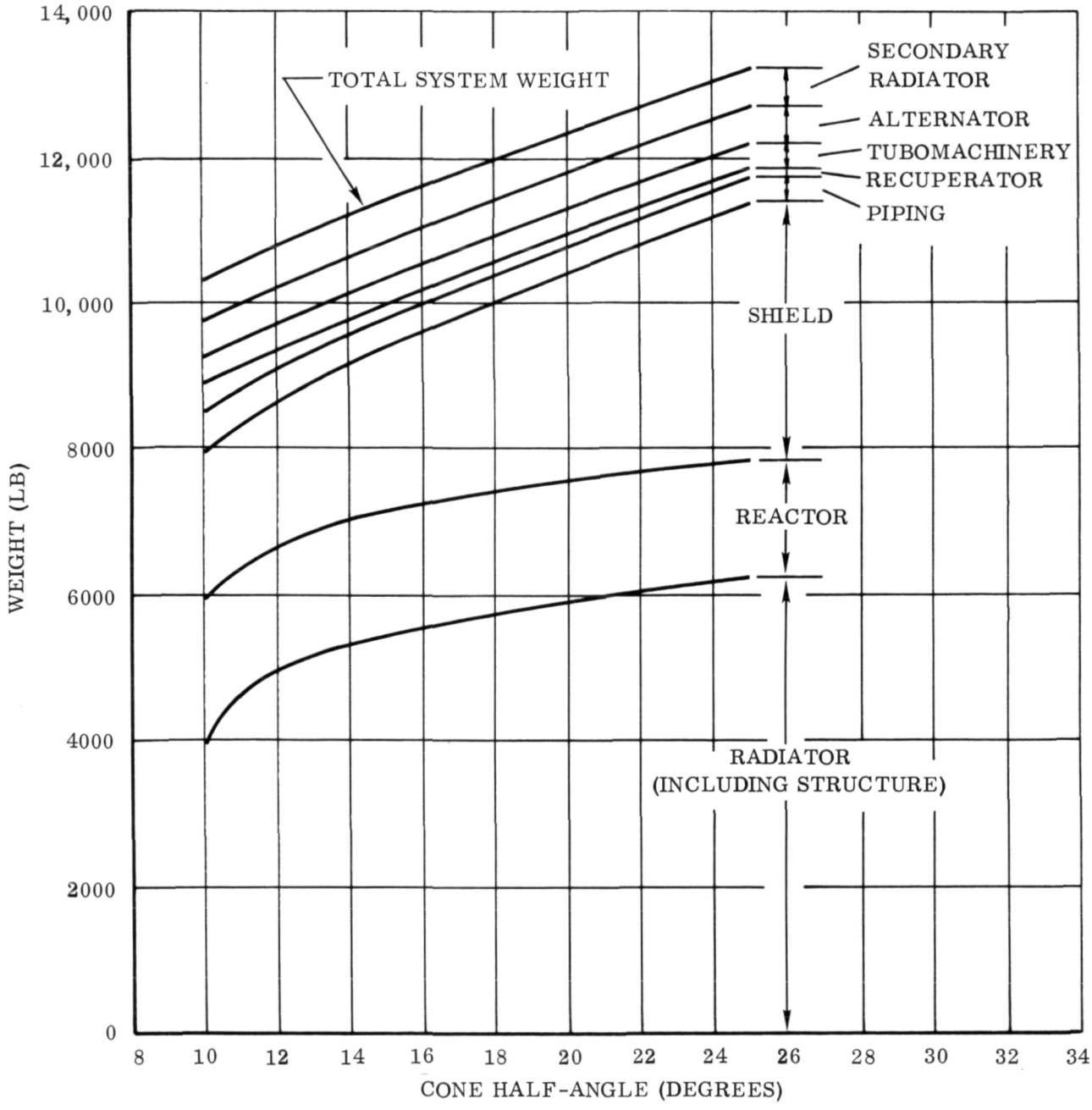

Figure 5-3. System Weight Variation with Cone Angle-200 KWe Unmanned with Uniform Fuel Loaded Reactor

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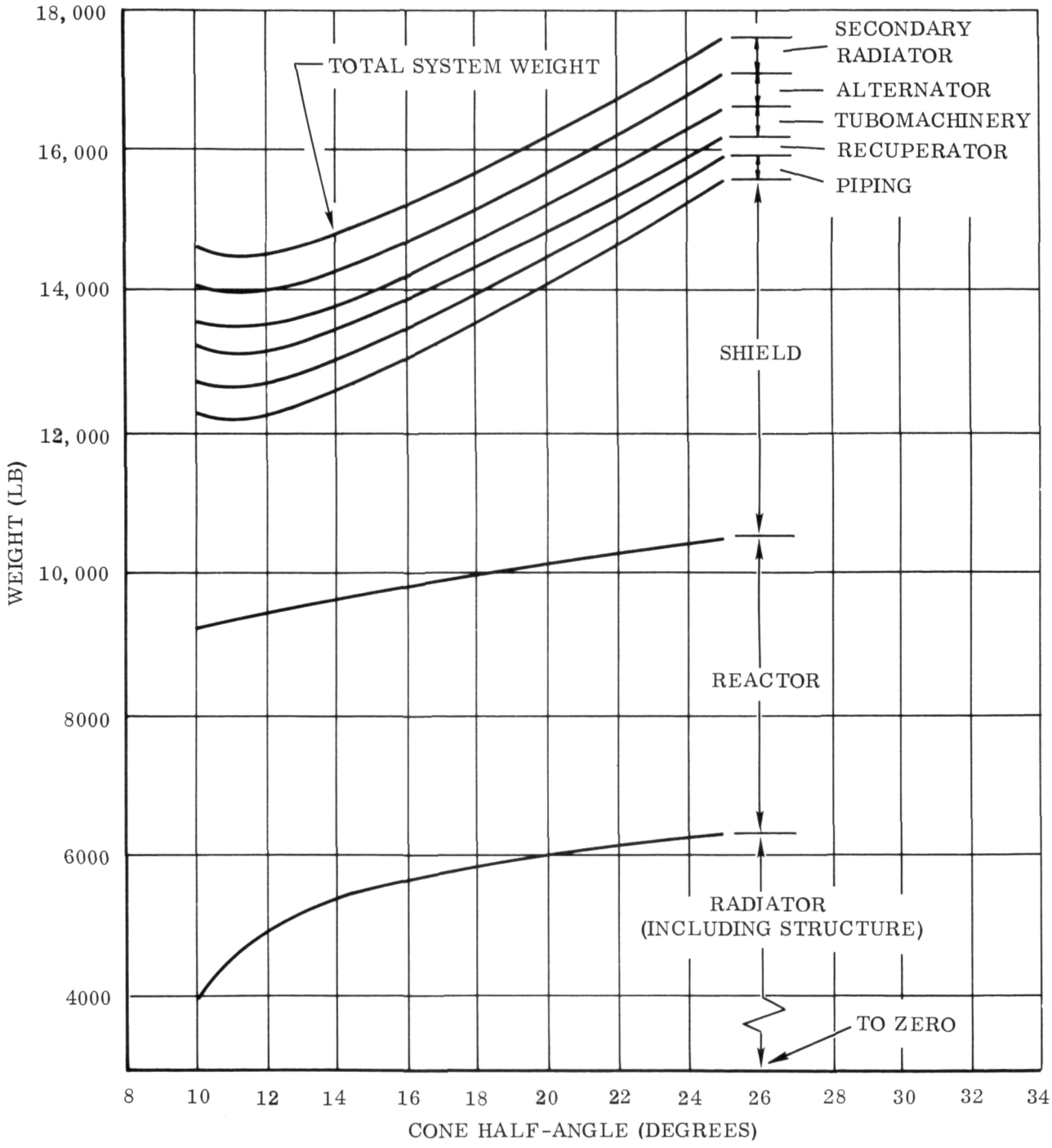

Figure 5-4. System Weight Variation with Cone Angle-200 KWe Unmanned System with Power-Flattened, Uniform-Diameter Cooling Passage Reactor

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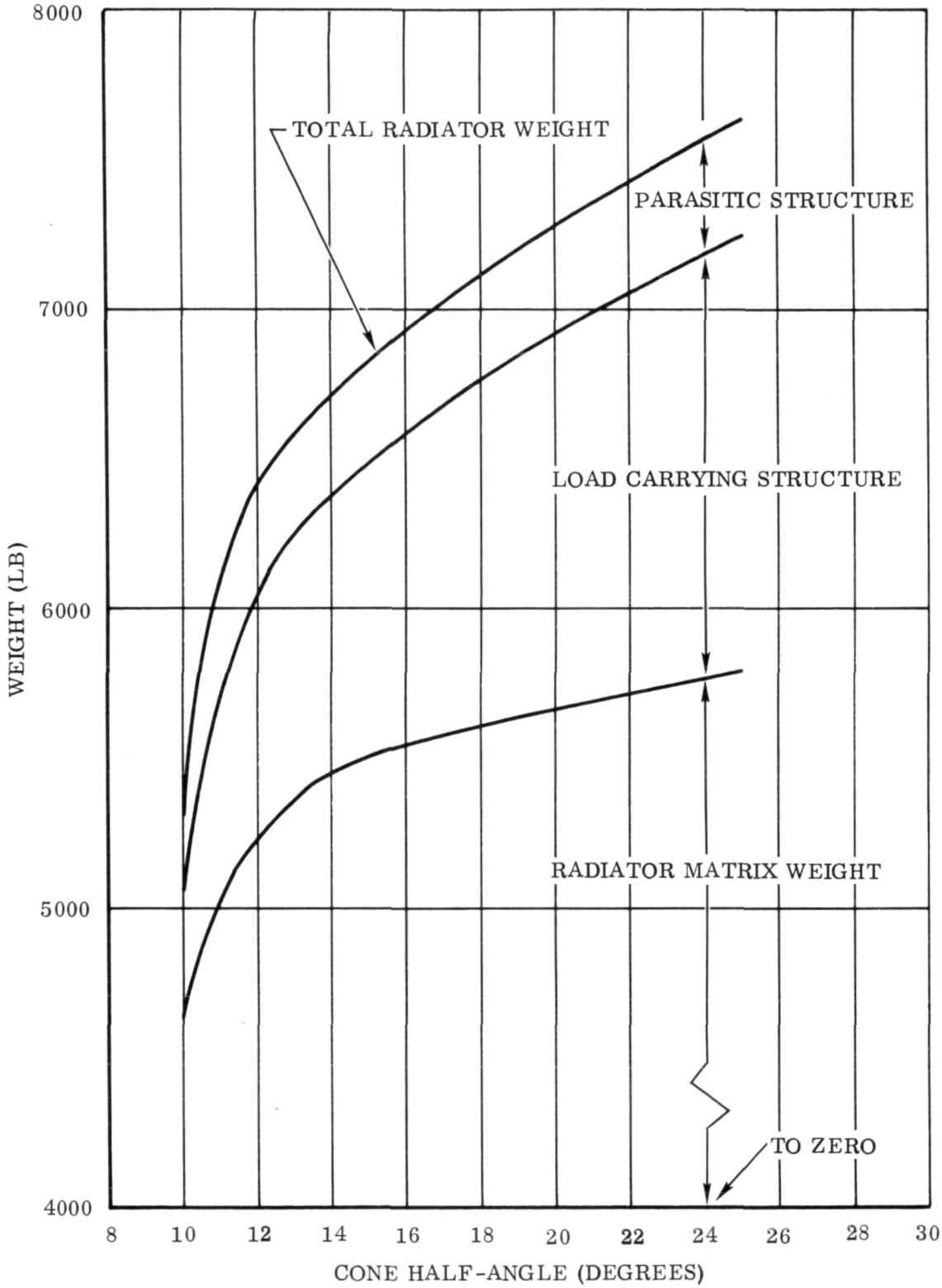

Figure 5-5. Radiator Weight Variation with Cone Angle-200 KWe Unmanned System with Uniform Fuel Loaded Reactor

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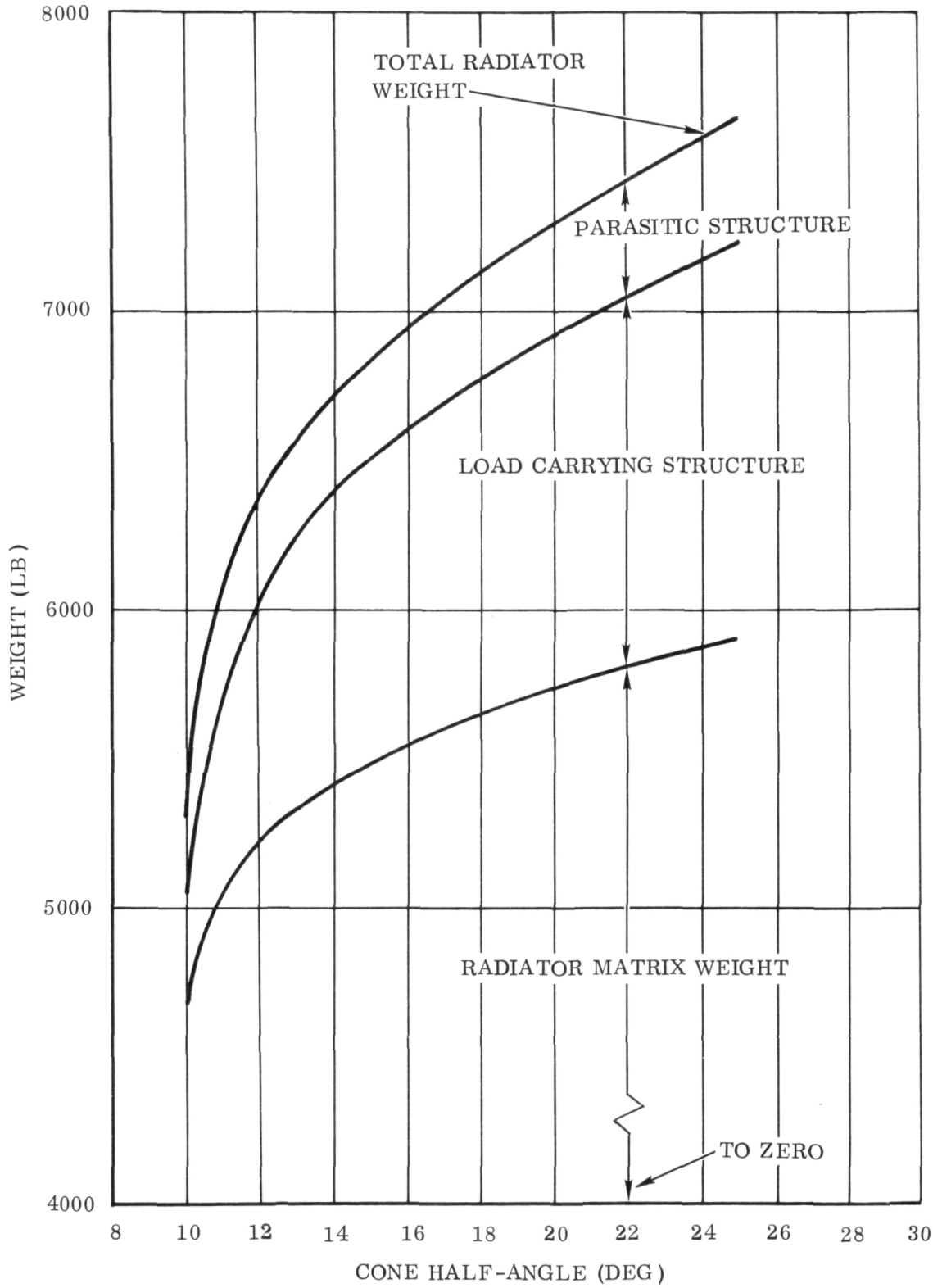

Figure 5-6. Radiator Weight Variation with Cone Angle-200 KWe Unmanned System with Power-Flattened, Uniform-Diameter Cooling Passage Reactor

5.3 RADIATOR DESIGN

Design of the radiators for the 200 KWe unmanned system are based on the requirements as determined by the cycle optimization program. Preliminary radiator weights are computed from the radiator thermal and structural models in the cycle program. These weights are used in determining the optimum cycle conditions. The Spartan computer program is used to perform the detail radiator design and weight analysis. The following are the radiator specifications determined by the cycle optimization.

- Thermal Load
- Radiating Area
- Gas Inlet Temperature
- Gas Outlet Temperature
- Pressure Loss Ratio

Further refinements on the structural requirements are determined performing a structural analysis of the radiator considered as a shell subjected to shear and compression buckling forces.

To simplify the feed-line network and thereby reduce the associated weight and pressure drops, headers spanning one-half the vehicle circumference are used. Feed-lines run parallel to the longitudinal axis of the vehicle along the inner radiator surface and are supported at each header ring. Differential thermal expansion along the axis of the feed lines is accommodated by a bellows section at each header intersection. The joints include an internal sleeve to minimize pressure losses and maintain alignment. Meteoroid protection for the feed-lines and headers is provided by means of thin-walled bumpers. Multifoil-radiation shielding and low emissivity coatings are used on the inner surfaces of the radiator to control the internal thermal radiation. The turbomachinery and ducting are similarly insulated.

5.3.1 RADIATOR THERMAL ANALYSIS

The primary radiator selected for use on the 200 KWe unmanned vehicle is a 6-panel 3-bay arrangement. Tube lengths in each panel are varied to provide equal area and equal heat

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rejection from each panel. The thermal analysis was performed on an equivalent cylindrical radiator using equal size panels. This method of analysis facilitates the handling of feed line networks and pressure loss calculations. Errors incurred by this approximation have been found to be on the order of 1% or less. Figure 5-7 illustrates schematically the primary radiator arrangement as analyzed by the Spartan program. Table 5-3 summarizes the results of the thermal analyses. The parameters presented in this table are results of the thermally optimized radiator and are not necessarily sufficient to satisfy the structural requirements.

The secondary radiator heat load is sized to provide cooling for the alternator, pumps and miscellaneous functions. A total thermal load of 50 KW was estimated and an area of 300 ft^2 at the upper end of the vehicle is provided. Inlet fluid temperature to the radiator is taken as 400^{o}F. For purposes of optimization, the trade-off between radiator weight and pumping requirements was made by assuming a pump efficiency of 30% and a system specific weight of 52 lbs/KWe. To eliminate freezing problems, an organic coolant is used in this loop. Meteoroid protection for the secondary radiator system is based on a 0.98 probability of no puncture for 10,000 hours.

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Table 5-3. Summary of Radiator Parameters for 200 KWe Unmanned System

	Units	Radiator Primary	Secondary Radiator
Heat Rejected	KW	725	50
Area	Ft^2	1677	300
Gas Inlet Pressure	PSIA	165	---
No. of Panels	---	1.50	11.3
Header Length	Ft	25	12.3
Fluid Inlet Temp	^oF	850	400
Fluid Outlet Temp	^oF	424	371
Tube Spacing (Ave)	In.	6.25	4.9
Fin Thickness	In.	0.075	0.040
Tube Inside Dia.	In.	0.48	0.19
Smallest Feed Dia.	In.	5.25	1.2
Wt. of Fins	Lbs	1,729	170
Wt. of Tubes	Lbs	1,391	109
Wt. of Headers	Lbs	105	12
Wt. of Feeds	Lbs	156	19
Total Weight	Lbs	3,381	310
Fluid	---	Neon	ET-378
Hydraulic Pump Work	KW	---	0.13
Coolant Flow Rate	Lbs/Sec	6.57	3.84
Mean Time to Failure	Hrs	200,000	500,000
Sink Temp	^oF	-10	-10

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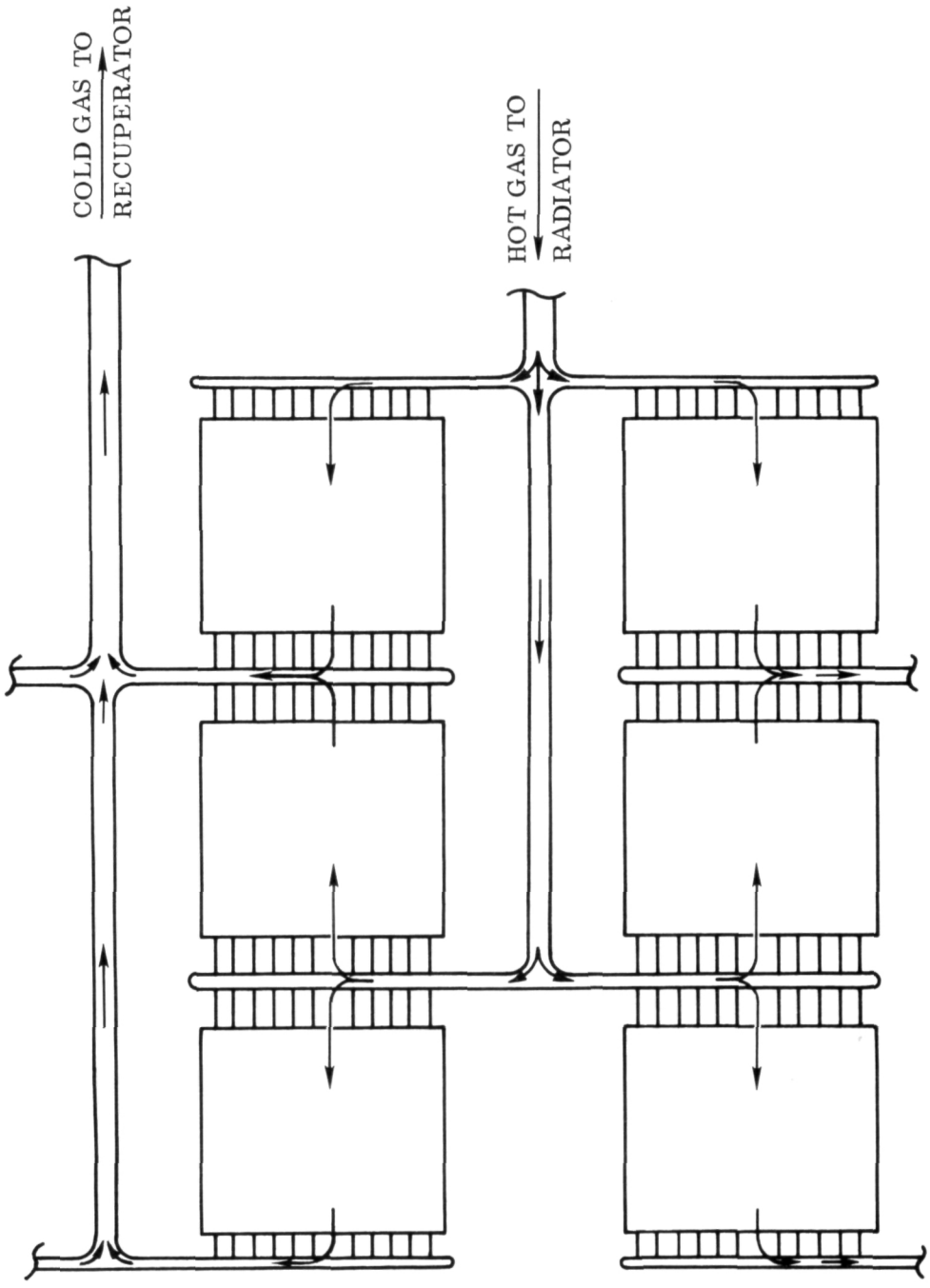

Figure 5-7. Piping Schematic of 200 KWe Unmanned System-Primary Radiator Loop

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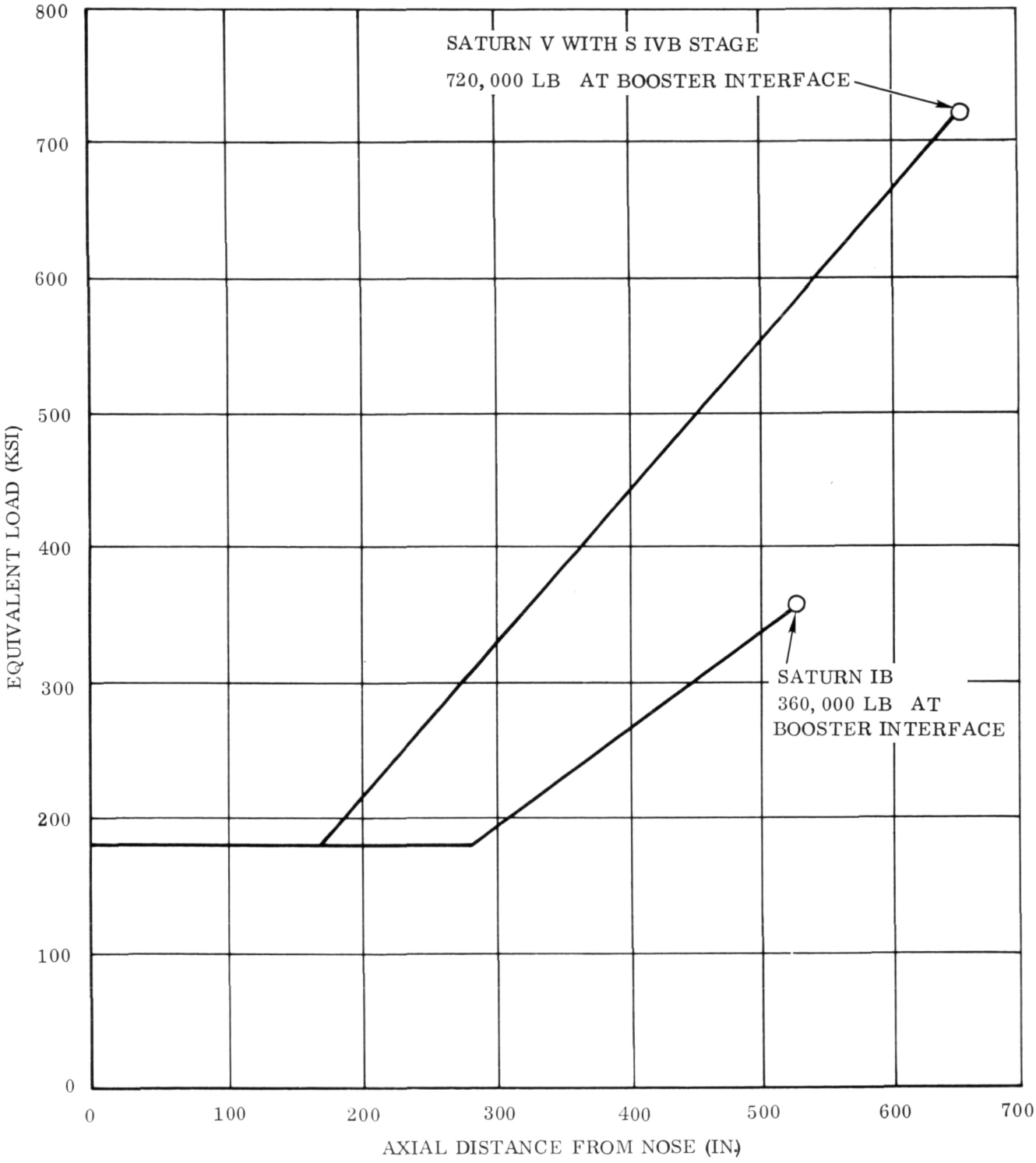

Figure 5-8. Radiator Structural Loading

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5.3.2 RADIATOR STRUCTURAL ANALYSIS

Structural adequacy of the radiator matrix is determined by performing a detailed load analysis. Inputs to this program include the radiator geometric factors as determined by the Spartan program and the equivalent mechanical loads found from the curves of Figure 5-8. With this data, the radiator is checked for margins of safety on general, local, and panel instability modes of failure. A radiation not showing positive margins is modified by one or more of the following means:

- Increase of Fin Thickness
- Decrease of Tube Spacing
- Addition of Stiffeners on Tubes
- Addition of Rings

The first two of these items are intimately related to the thermal performance of the radiator and changes of these variables may shift the thermal optimization point. In cases where significant changes are necessary, iteration between the thermal and structural programs were made to determine the optimum configuration.

The results of the structural analysis performed on the thermally optimized radiator are shown in Table 5-4. The only structural addition to these designs is the addition of rings as required to give a positive margin of safety for panel stability. With the exception of the upper primary bay, negative margins of safety occur for local instability and, in the case of the secondary radiator, general instability also.

The results of the structural analysis with tube stiffeners and increased fin thickness on the different radiators are shown in Table 5-5. The lower and center primary radiator bays required only a slight increase in fin thickness. The total weight increase of the primary radiator system due to structural considerations is 485 pounds, 76 pounds of which results from increased fin thickness and the remainder from rings, tube stiffeners and parasitic structure. Table 5-6 summarizes the weights of the added structure to each of the radiator bays.

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Table 5-4. Summary of Structural Analysis of Thermally Optimized Radiator

	Units	Primary Radiator			Secondary Radiator
		Upper Bay	Center Bay	Lower Bay	
Equivalent Load (top)	KSI	270	455	590	200
Equivalent Load (bottom)	KSI	455	590	723	270
Tube Length	ft	14.1	10.0	8.5	12.0
Tube Spacing	in.	6.25	6.25	6.25	4.90
Fin Thickness	in.	0.075	0.075	0.075	0.040
RF (See Figure 5-9)	in.	0.516	0.516	0.516	0.300
TAT (See Figure 5-9)	in.	0.079	0.079	0.079	0.088
TLT (See Figure 5-9)	in.	0.015	0.015	0.015	0.015
Upper Cone Diameter	in.	120	183	223	67.6
Lower Cone Diameter	in.	183	223	260	120
Tapered Fins	---	yes	yes	yes	yes
Tube Stiffener Height	in.	0	0	0	0
Tube Stiffener Width	in.	0	0	0	0
Weight of Tube Stiffeners	lbs	0	0	0	0
No. of Rings Added	---	4	2	2	7
Height of Rings Added	in.	1.4	2.0	2.7	1.2
Weight of Rings Added	lbs	36	35	55	17.30
Margin of Safety for Panel Instability	---	0.53	0.01	0.31	0.07
Margin of Safety for Local Instability (top)	---	0.12	-0.02	-0.12	-0.80
Margin of Safety for Local Instability (center)	---	0.04	-0.07	-0.15	-0.78
Margin of Safety for Local Instability (bottom)	---	0.01	-0.10	-0.17	-0.73
Margin of Safety for General Instability (top)	---	0.87	0.52	0.40	0.03
Margin of Safety for General Instability (center)	---	0.52	0.37	0.28	0.002
Margin of Safety for General Instability (bottom)	---	0.22	0.23	0.18	-0.012

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Table 5-5. Results of Structural Analysis of 200 Kwe Unmanned System Radiators

	Units	Primary Radiator		Secondary
		Center Bay	Lower Bay	Radiator
Equivalent Load (Top)	KS1	445	590	200
Equivalent Load (BTM)	KS1	590	723	270
Tube Length	Ft.	10	8.5	12.0
Tube Spacing (Average)	In	6.25	6.25	4.90
Fin Thickness	In	0.080	0.080	0.075
RF (See Fig. 5-9)	In	0.516	0.516	0.300
TAT (See Fig. 5-9)	In	0.079	0.079	0.088
TLT (See Fig. 5-9)	In	0.015	0.015	0.015
Upper Cone Diameter	In	183	223	68
Lower Cone Diameter	In	223	260	120
Tapered Fins	-	Yes	Yes	Yes
Tube Stiffener Height	In	0	0.50	0
Tube Stiffener Width	In	0	0.08	0
Weight of Tube Stiffeners	Lbs.	0	49	0
No. of Rings Added	-	2	1	6
Height of Rings Added	In	2.0	2.4	0.90
Weight of Rings Added	Lbs.	37	25.8	21.3
Margin of Safety for Panel Instability	-	0.04	0.08	0.12
Margin of Safety For Local Instability (Top)	-	0.15	0.09	0.04
Margin of Safety For Local Instability (Center)	-	0.10	0.05	0.21
Margin of Safety For Local Instability (Bottom)	-	0.07	0.02	0.53
Margin of Safety For General Instability (Top)	-	0.58	0.53	0.48
Margin of Safety For General Instability (Center)	-	0.42	0.41	0.31
Margin of Safety For General Instability (Bottom)	-	0.28	0.29	0.26

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Table 5-6. 200 KWe Unmanned System Summary of Structural Weight Additions

	Units	Primary Radiator Bays			Secondary Radiator
		Upper	Center	Lower	
Additional Fin Thk. Req'd.	In.	0	0.005	0.005	0.035
Additional Weight of Fins	Lbs	0	38	38	150
Ring Weight	Lbs	36	37	26	21
Tube Stiffener Weight	Lbs	0	0	49	0
Parasitic Structure Weight	Lbs	87	87	87	44
Total Structure Weight	Lbs	123	162	200	215

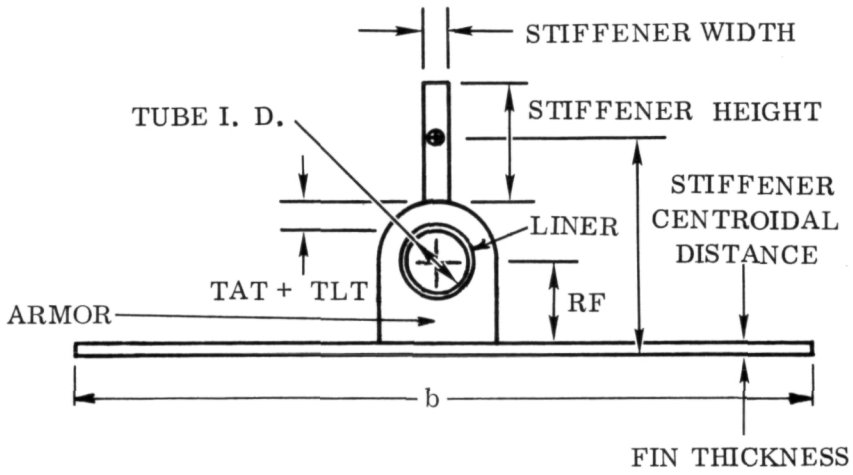

Figure 5-9. Section Nomenclature

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Table 5-7. Summary of 200 Kwe Unmanned System Recuperator Design

Recuperator Material	---	Nickel
Gas	---	Neon
Mass Flow Rate	Lbs/Hr	23662
Inlet Pressure (Side 1)	PSIA	160
Inlet Pressure (Side 2)	PSIA	295
Inlet Temperature (Side 1)	^{o}F	1698
Inlet Temperature (Side 2)	^{o}F	762
Outlet Temperature (Side 1)	^{o}F	847
Outlet Temperature (Side 2)	^{o}F	1613
Plate Thickness	In	0.006
Fin Thickness	In	0.004
Shell Thickness	In	0.006
Plate Spacing (Side 1)	In	0.35
Plate Spacing (Side 2)	In	0.24
Fin Spacing (Side 1)	In	0.035
Fin Spacing (Side 2)	In	0.50
Core Length	Ft	1.80
Core Width	Ft	0.87
Core Height	Ft	2.93
Heat Transfer Coefficient	$\frac{BTU}{HR\text{-}FT^{2}\text{-}^{o}F}$	31.9
Effectiveness	%	90.9
Pressure Loss Ratio (Each Side	%	1.11
Core Weight	Lbs	426
Manifold & Shell Weight	Lbs	209
Total Weight	Lbs	635

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The secondary radiator is seen to require a fin thickness almost double that of the thermally optimum radiator. Further analysis using the Spartan computer code shows an optimized radiator of this fin thickness and tube spacing to be capable of rejecting approximately 0.184 KW/Ft^2. The 300 ft^2 radiator provided, therefore, has a thermal capability of approximately 55 KW. Since the thermal load of this system has not been determined to this degree of accuracy, no charge in the configuration was made.

5.4 RECUPERATOR DESIGN

Preliminary recuperator characteristics were determined from the analytical model in the cycle program. As with the radiators, system trade-offs are performed on the basis of this model and details of the design are determined from a separate recuperator design program from which the analytical model was derived.

The recuperator used in the Brayton Cycle systems is a counter-flow heat exchanger of the type illustrated by Figure 5-10. Sizing of the recuperator is such as to provide the effectiveness and pressure loss ratios determined as optimum by the cycle program. In the case of the 200 KWe unmanned system, a recuperator with an effectiveness of 90.6% and a pressure loss ratio of 1.11% at a weight of approximately 430 pounds was required for the optimized cycle point. These requirements, along with the appropriate inlet temperatures and mass flow rates, were used as boundary conditions. Results of detailed design of the recuperator are summarized in Table 5-7.

A cursory structural analysis was performed on the recuperator core to ascertain margins of safety for burst pressures and crippling of the internal fins due to pressure differentials in the core. Considering the external shell between plates as simply supported, a conservative assumption, the shell exhibits a margin of safety of 3.15 for this failure mode. The fin buckling analysis examined the condition in which a bond failure occurs on one fin on the high pressure side and the force due to the 150 psi pressure differential is resisted by the compression of the fin on the low pressure side. Assuming pinned ends, a margin of safety of 0.18 is found for the buckling mode of failure. In reality, the end condition of the fin lies somewhere between pinned and fixed, hence the analysis is

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conservative. The bending resistance of the 0.006-inch splitter plate separating the high and low pressure sides of the recuperator would add additional strength.

5.5 OFF-OPTIMUM PERFORMANCE

The sensitivity of the powerplant specific weight to off-optimum conditions was determined by evaluating system weights for powerplants whose component interface variables were all fixed at the optimum condition, except for the one under consideration. The curves presented in this section represent 200 KWe powerplants with each component individually operating slightly off-optimum, and the remainder of the components operating with optimum performance specifications, only sized to deliver 200 KWe for the new system.

Since the radiator is limited to 1677 ft^2 because of the conical design, the varying heat rejection requirement is met by varying the fin efficiency. The variation in total radiator weight over the range of reactor pressure drops between 1.0% and 1.6% is 11 pounds. The radiator for the system with a 2.0% reactor pressure drop is 80 pounds heavier than that for the optimum system.

The sensitivity to the turbine pressure ratio is shown in Figure 5-12. It is seen that the variation in system specific weight is negligible for turbine pressure ratios between 1.6 and 2.0. Thus a wide latitude exists for the turbomachinery requirements. Figures 5-11 through 5-17 show the sensitivity of specific weight to each of the optimized variables about the design point of the system using a uniformly loaded fuel temperature flattened reactor. Figure 5-11 shows that decreasing reactor fractional pressure loss results in an increase in system specific weight, while increases in fractional pressure loss result in no appreciable change in system specific weight until the reactor pressure drop exceeds 2%. The optimization procedure selected the low end of a system weight plateau. If detailed reactor heat transfer and pressure drop design studies show it to be difficult to achieve the system design pressure drop, then little system weight penalty results from reactor designs at up to 2% pressure drop.

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The possibility exists that lower pressure ratio compressors might be developed with higher efficiencies since compressor performance summary maps show improved performance low pressure ratio for machines. The fact that at a turbine pressure ratio of 1.6 (and a compressor pressure ratio of 1.69) the system weight is still essentially that of the optimum system supports the feasibility of the use of neon as the working fluid.

The sensitivity to compressor inlet temperature is shown in Figure 5-13. Variations off optimum result in large changes in overall system specific weight. Figure 5-14 shows the sensitivity to radiator fractional pressure drop. It is seen that the design point lies in the middle of a plateau and that larger pressure drops have little influence on overall system weight. The sensitivity to recuperator effectiveness, shown in Figure 5-15, is more pronounced, and a clearer optimum exists. The sensitivity to recuperator fractional pressure drop (each side) is shown in Figure 5-16. A definite optimum exists, but the penalties for off-optimum design are not great. Figure 5-17 shows the sensitivity of system specific weight to the ducting diameter. Smaller duct sizes result in intolerable penalties in terms of pressure drop. The weight penalties associated with larger duct sizes is not as great.

Similar sensitivity curves were obtained for systems using the larger, power flattened, reactor, and are shown in Figures 5-18 through 5-24. In each case the sensitivities exhibited the same shapes. Thus the conclusions that the sensitivities to off optimum pressure drops and pressure ratios are small, while sensitivities to compressor inlet temperature, ducting size, and recuperator effectivenss are important remain valid, independent of reactor size.

Sensitivity to parasitic fractional pressure loss was determined. The system specific weight has been found not to be very sensitive to the off-optimum component pressure drop design requirements. A similar result was found for the parasitic loss. Figure 5-25 shows the sensitivity to parasitic fraction pressure drop for both the uniform fueled, temperature-flattened reactor and the power-flattened reactor. The sensitivity of system specific weight increases with increasing pressure loss. The sensitivity of the reference design is 1 lb/KW per 1% parasitic pressure loss. For 1% parasitic loss, the sensitivity is 1-1/4 lb/KW per 1%,

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and is 2 lbs/KW at 2%. It can be concluded that, at a turbine inlet temperature of 2200°F, the sensitivity of the system specific weight to parasitic pressure drop is not great, and is comparable with weight uncertainties associated with variations between preliminary design and finished system.

The sensitivity of system specific weight to sink temperature is shown in Figure 5-26. It is seen that sink temperature has little effect on system weight at low sink temperatures. At high sink temperatures an appreciable sensitivity to sink temperature exists.

5.5.1 EFFECT OF REACTOR DIAMETER

In order to show the influence of reactor diameter on system specific weight for reactors other than the uniformly fueled, temperature flattened, design, and the power flattened design with uniform coolant passages, systems were evaluated using the same fractional pressure drop-core diameter variation as was used for the power flattened reactor. Figure 5-27 shows the resulting variation in specific weight plotted against reactor core diameter at 2% pressure drop. The comparison shows a large sensitivity to core diameter, increasing with reactor size. The major items effecting this variation are the reactor and shield weight.

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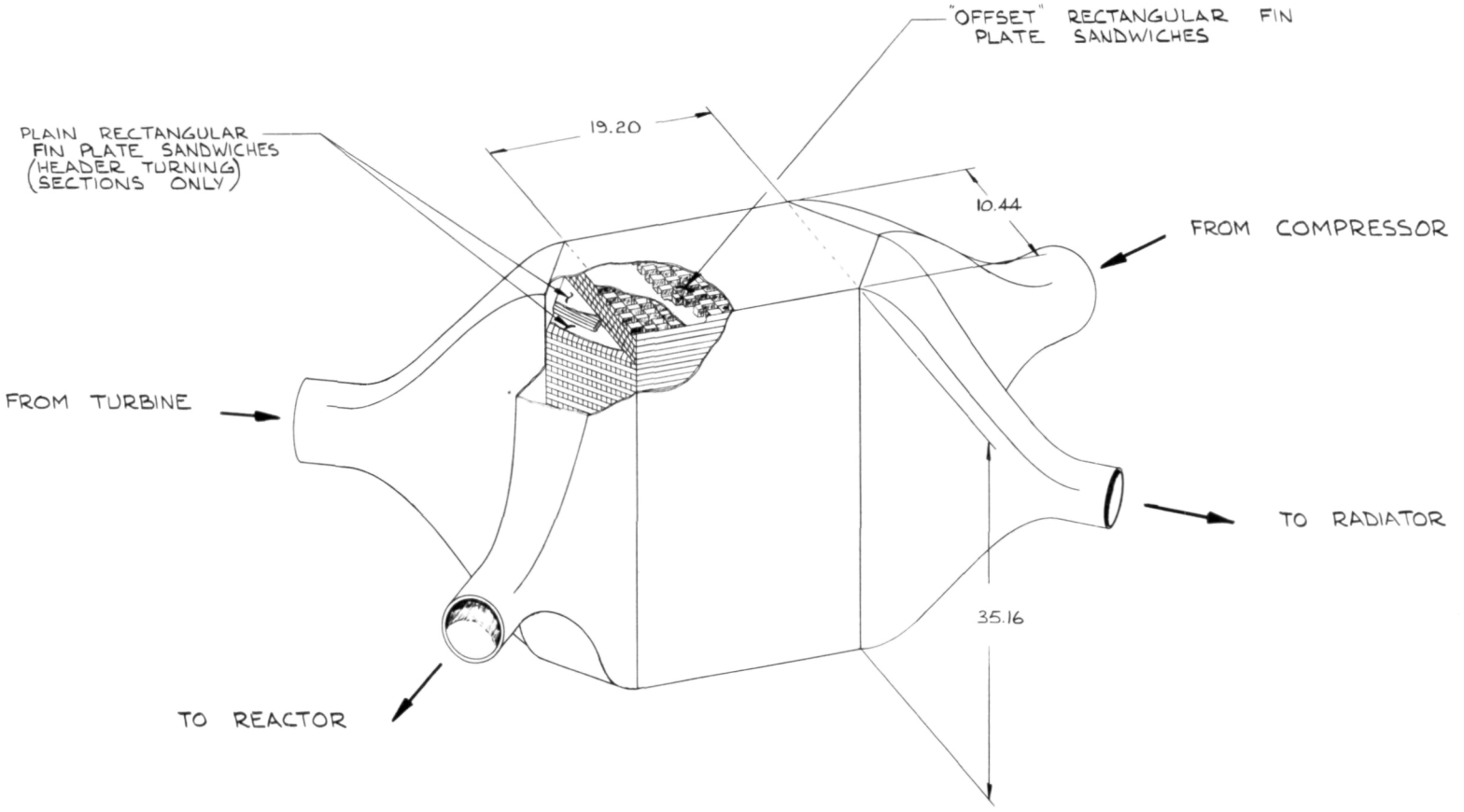
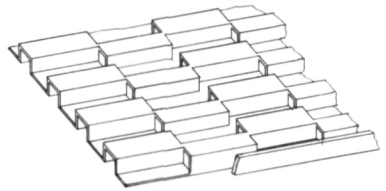


RECUPERATOR
1~ LOOP BRAYTON CYCLE



"OFFSET" RECTANGULAR FINS (TYPICAL)

Figure 5-10. Recuperator Design

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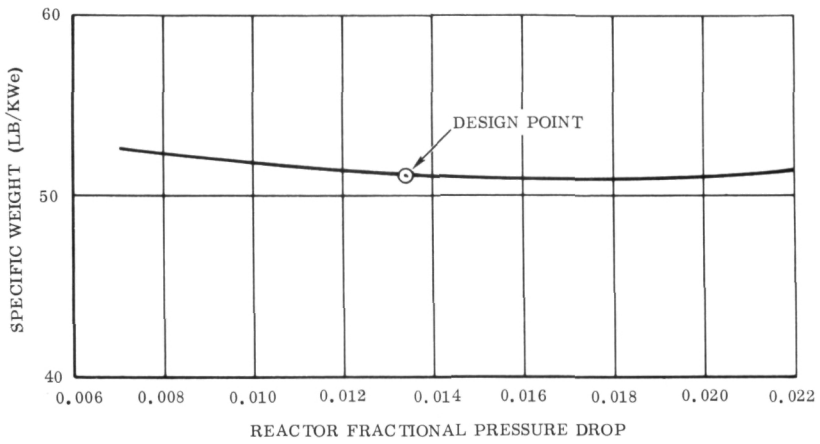

Figure 5-11. Sensitivity of System Specific Weight to Reactor Fractional Pressure Drop - Uniform Fuel Loaded Reactor

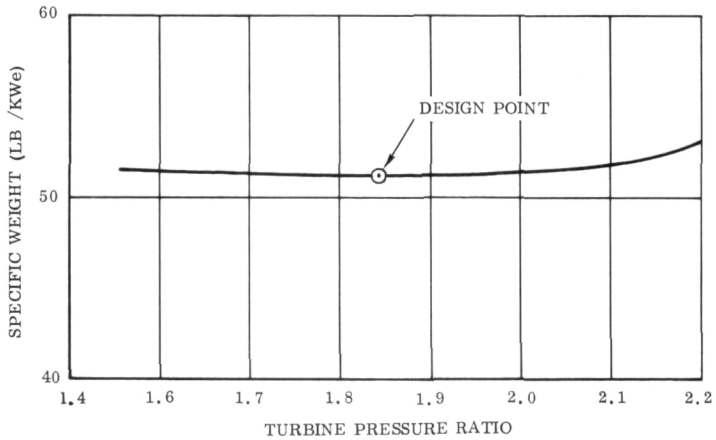

Figure 5-12. Sensitivity of System Specific Weight to Turbine Pressure Ratio - Uniform Fuel Loaded Reactor

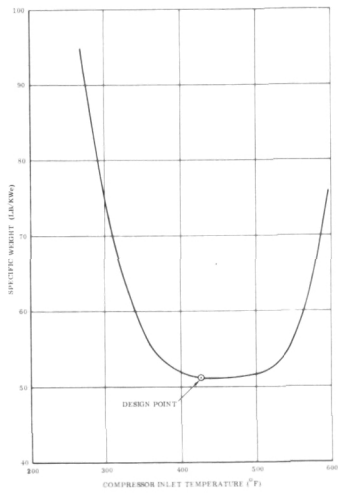

Figure 5-13. Sensitivity of System Specific Weight to Compressor Inlet Temperature - Uniform Fuel Loaded Reactor

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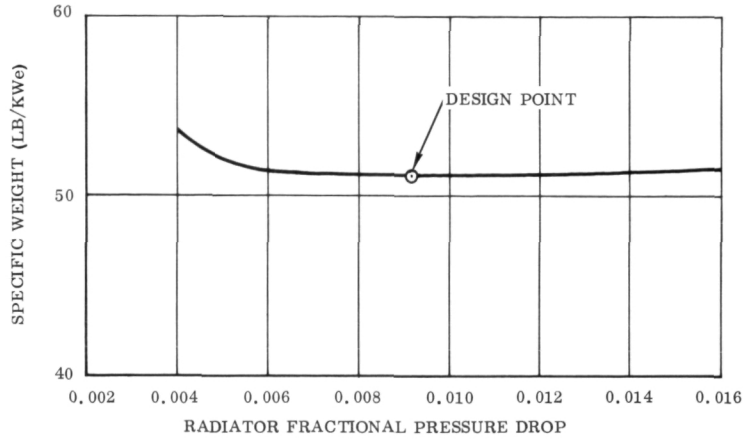

Figure 5-14. Sensitivity of System Specific Weight to Radiator Fractional Pressure Drop - Uniform Fuel Loaded Reactor

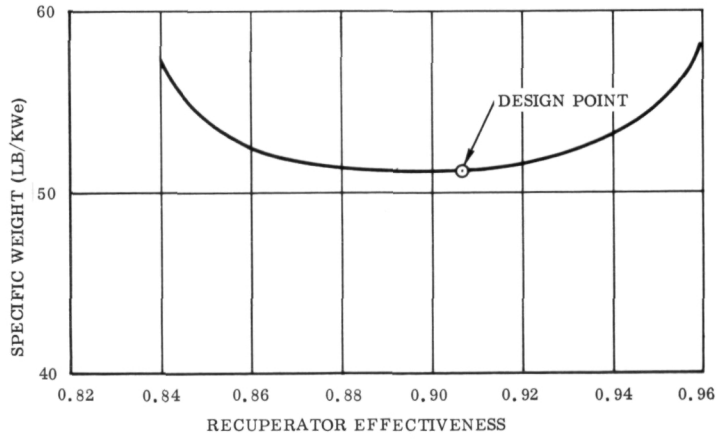

Figure 5-15. Sensitivity of System Specific Weight to Recuperator Effectiveness - Uniform Fuel Loaded Reactor

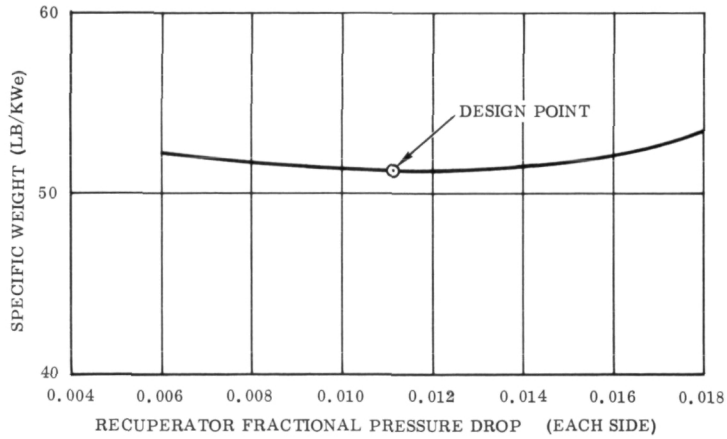

Figure 5-16. Sensitivity of System Specific Weight to Recuperator Pressure Drop (Each Side) - Uniform Fuel Loaded Reactor

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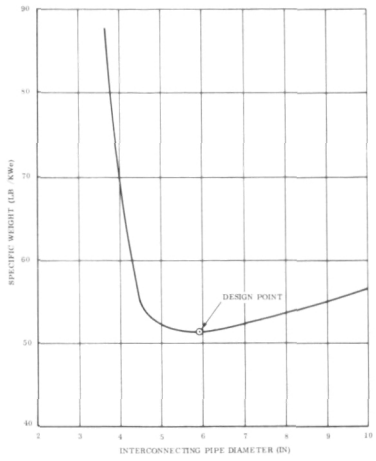

Figure 5-17. Sensitivity of System Specific Weight to Interconnecting Pipe Diameter - Uniform Fuel Loaded Reactor

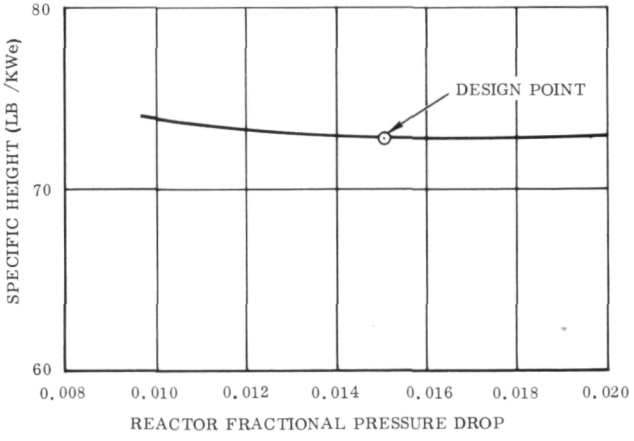

Figure 5-18. Sensitivity of System Specific Weight to Reactor Fractional Pressure Drop - Power Flattened Reactor

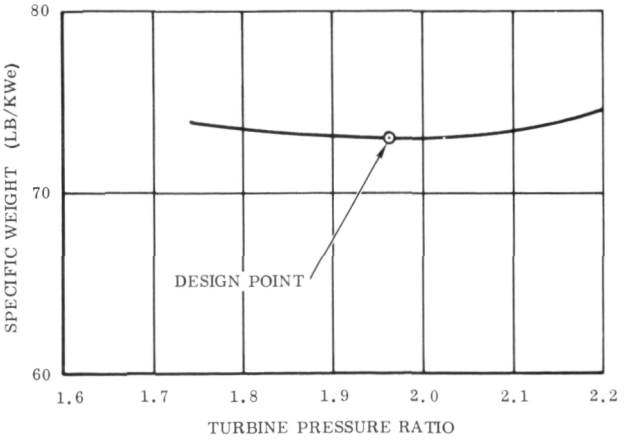

Figure 5-19. Sensitivity of System Specific Weight to Turbine Pressure Ratio - Power Flattened Reactor

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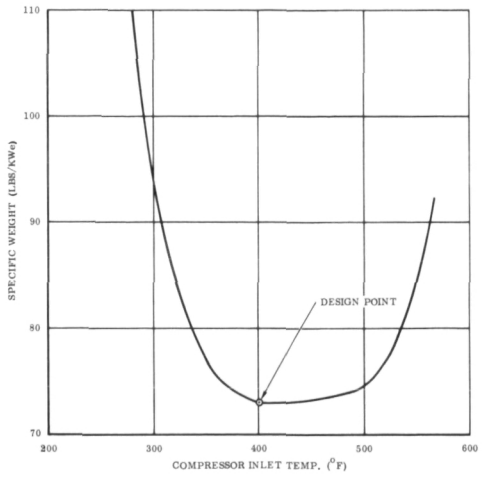

Figure 5-20. Sensitivity of System Specific Weight to Compressor Inlet Temperature - Power Flattened Reactor

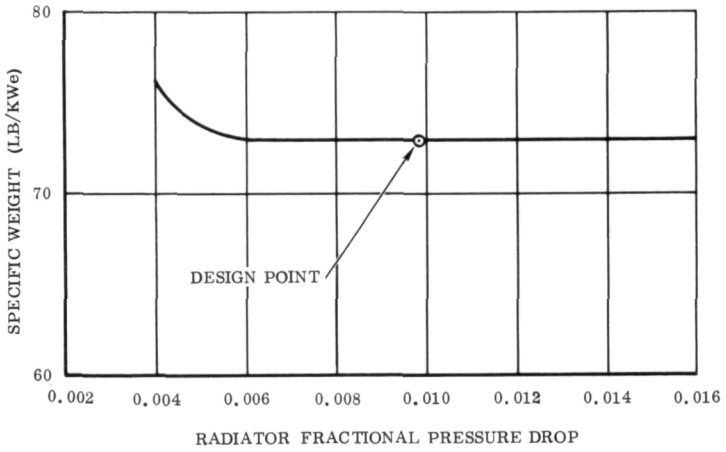

Figure 5-21. Sensitivity of System Specific Weight to Radiator Fractional Pressure Drop - Power Flattened Reactor

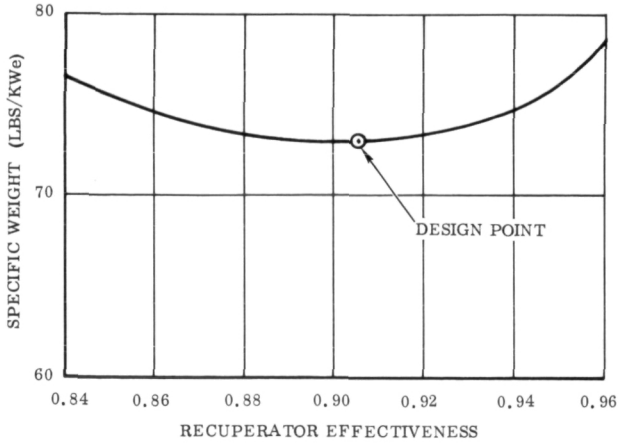

Figure 5-22. Sensitivity of System Specific Weight to Recuperator Effectiveness - Power Flattened Reactor

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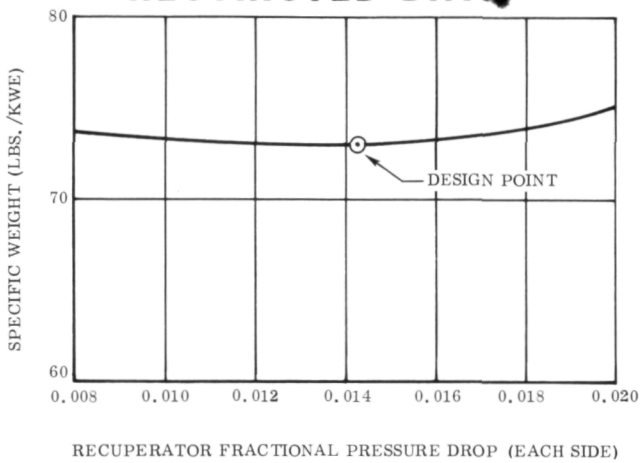

Figure 5-23. Sensitivity of System Specific Weight to Recuperator Pressure Drop (Each Side) - Power Flattened Reactor

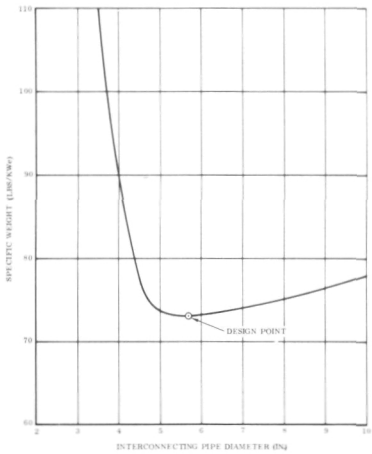

Figure 5-24. Sensitivity of System Specific Weight to Interconnecting Pipe Diameter - Power Flattened Reactor

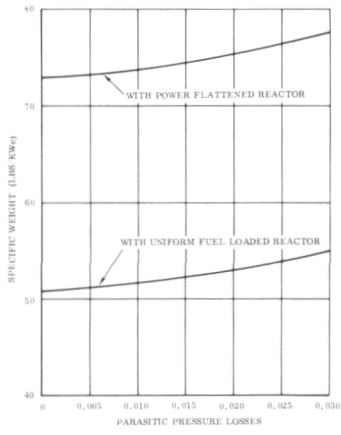

Figure 5-25. Sensitivity of System Specific Weight to Parasitic Pressure Losses - with Power Flattened Reactor or with Uniform Fuel Loaded Reactor

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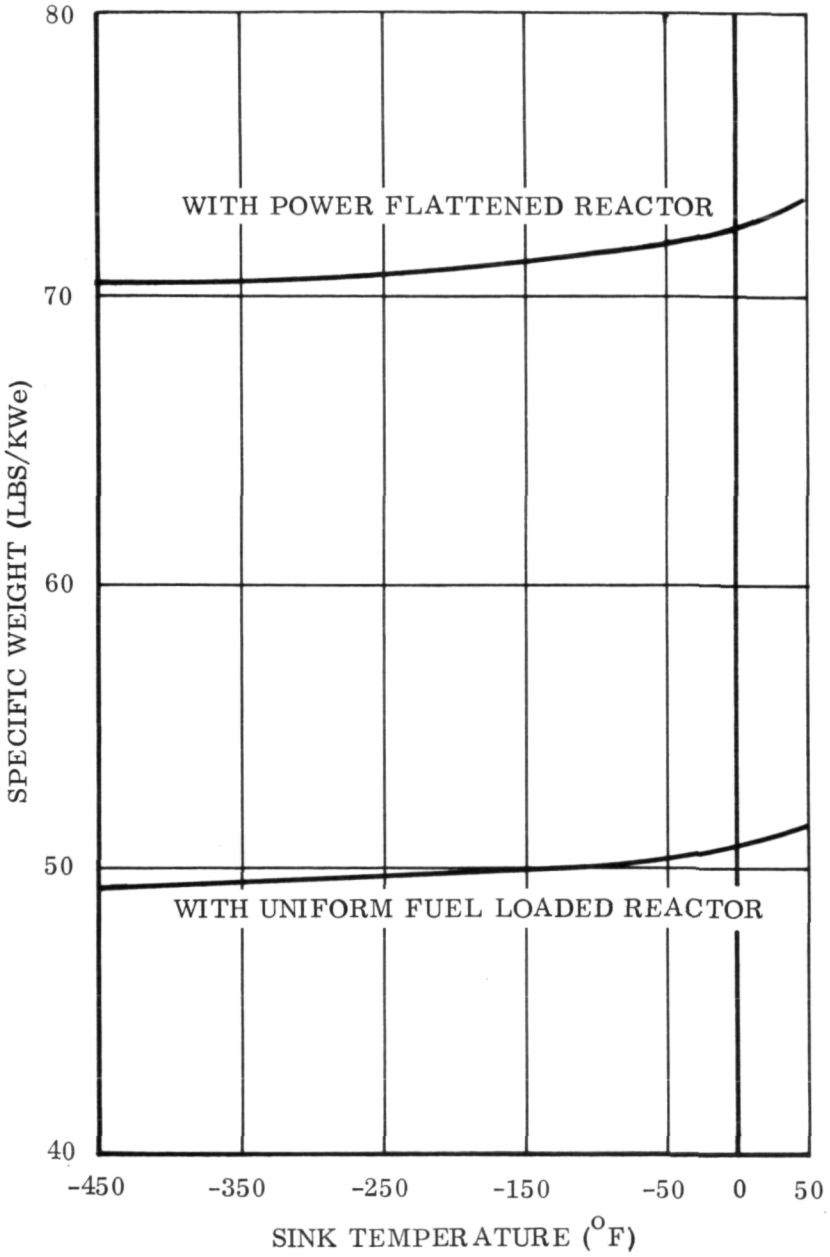

Figure 5-26. Sensitivity of System Specific Weight to Sink Temperature - with Power Flattened Reactor or with Uniform Fuel Loaded Reactor

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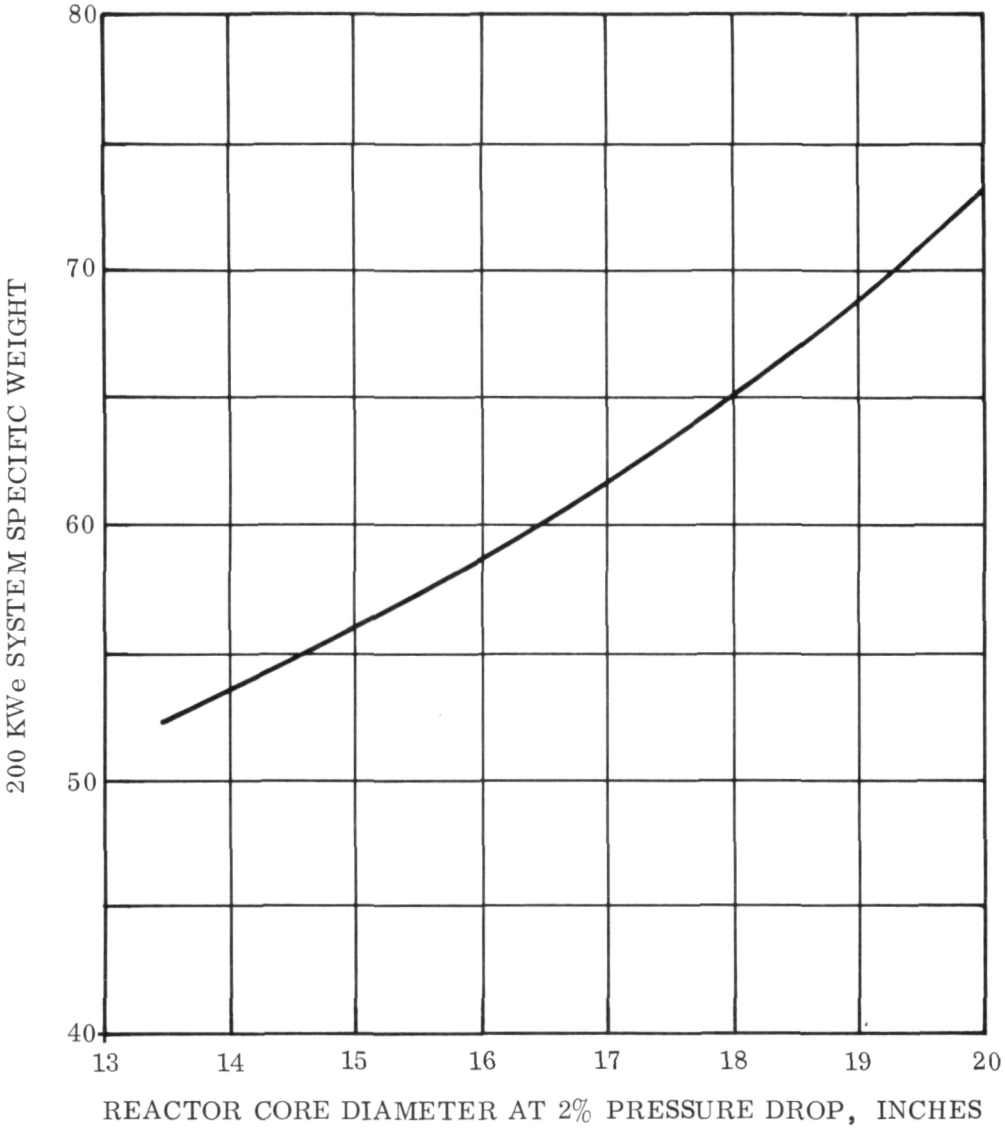

Figure 5-27. Effect of Reactor Diameter on System Weight

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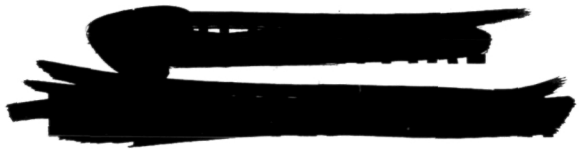

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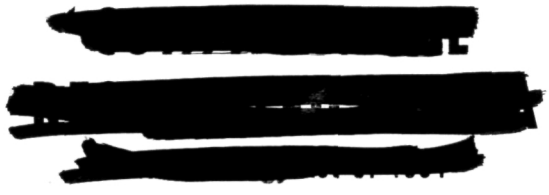
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